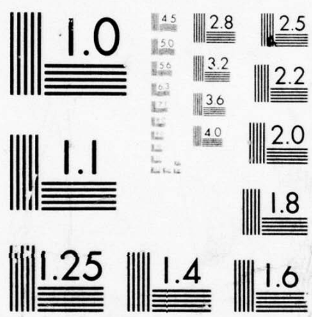
AD-A051 333 RCA GOVERNMENT SYSTEMS DIV MOORESTOWN N J MISSILE AND--ETC F/G 17/9
CCD SIGNAL PROCESSOR STUDY.(U)
DEC 77 L W MARTINSON, B P GAFFNEY, G J MAYER F30602-76-C-0280

UNCLASSIFIED RADC-TR-77-422 NL

1 OF 4

AD
A051 333



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

2

RADC-TR-77-422
Final Technical Report
December 1977

CCD SIGNAL PROCESSOR STUDY

Lloyd W. Martinson
Brian P. Gaffney
Gerard J. Mayer

RCA/Government and Commercial Systems

Approved for public release; distribution unlimited.

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

This report contains a large percentage of machine-produced copy which is not of the highest printing quality but because of economical consideration, it was determined in the best interest of the government that they be used in this publication.

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-77-422 has been reviewed and is approved for publication.

APPROVED: William Lee Simkins, Jr.
WILLIAM LEE SIMKINS, JR.
Project Engineer

APPROVED: Joseph L. Ryerson
JOSEPH L. RYERSON
Technical Director
Surveillance Division

FOR THE COMMANDER: John P. Huss
JOHN P. HUSS
Acting Chief, Plans Office

If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC (OCTS) Griffiss AFB NY 13441. This will assist us in maintaining a current mailing list.

Do not return this copy. Retain or destroy.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-77-422	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CCD SIGNAL PROCESSOR STUDY		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report, May 1976 - May 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Lloyd W. Martinson, Brian P. Gaffney, Gerard J. Mayer		8. CONTRACT OR GRANT NUMBER(s) F30602-76-C-0280
9. PERFORMING ORGANIZATION NAME AND ADDRESS RCA/Government ~~and Commercial~~ Systems, Missile and Surface Radar Division, Moorestown, NJ 08057		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62702F 45060010C
11. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center (OCTS), Griffiss AFB, New York 13441		12. REPORT DATE December 1977
		13. NUMBER OF PAGES 314
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

18 19 6 9 10 15 16 17 11 12 314p. 01 Partel call 405296

16. DISTRIBUTION STATEMENT (of this Report)

Approved for release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

Project Engineer: William L. Simkins (OCTS)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Charge Coupled Devices, Signal Processing, Radar, Satellite, Surveillance, Matched Filters, Coherent Integrators, Spectrum Analyzers, Signal-to -Noise Ratio, Dynamic Range, Sidelobes, Computer Simulation, Performance Level, Delay Lines, Storage, Corner Turning Memories, Bandwidth, Programmability.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a study of the application of charge coupled devices (CCD's) to radar signal processing systems. The particular radar problem considered was the detection of satellites at ranges of up to 25,000 NM. A CCD baseline design and tradeoffs are given for this problem. CCD devices were characterized in sufficient detail to construct an accurate computer simulation of their operation. The simulation included all known noise effects in CCD's in addition to the basic functional properties such as

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

405296

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

charge transfer inefficiency and dark current. Delay line and matched filter configurations were then synthesized from the CCD model and performance of various CCD subsystems ascertained as CCD parameters were varied. Parameter variations included CCD length, clock rate, gate size, tapped weight accuracy, charge transfer inefficiency, and temperature. Results are presented relating study results to achievable performance for various signal processing subsystems. Programmability, bandwidth limitations, sidelobe levels, dynamic range and signal-to-noise considerations are addressed.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

PREFACE

This report was prepared by RCA/Government and Commercial Systems Division, Missile and Surface Radar, Moorestown, NJ under USAF contract F30602-76-C-0280, Project 4506, Task 01 in response to contract item A002. This work was administered under the direction of Rome Air Development Center, OCTS, W. Simkins, Project Engineer.

Contributions to this final technical report were made by F.P. Papasso and G.R. Stevens in addition to the listed authors.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

EVALUATION

The CCD Signal Processing Study has investigated the applications, capabilities, and limitations of Charge Coupled Device (CCD) technology in long range radar signal processing systems. To be cost-effective, a long range radar system must be highly flexible in terms of power budgeting and waveform generation and processing. New technologies are being investigated for use in flexible and adaptable signal processors not only for new radar systems but also for cost-effective upgrading of existing systems. This effort has shown that CCD technology has promise in this area and has evaluated the tradeoffs for various signal processing applications and implementations. This work is in support of TPO R1C, "Surveillance Sensor Technology".

William Lee Simkins, Jr.
WILLIAM L. SIMKINS, Jr.
Project Engineer/OCTS

1.0 INTRODUCTION

The rapidly evolving technology of charge coupled devices (CCD's) holds promise for substantial reduction in the size, power consumption and ultimate cost of radar signal processors. The CCD Signal Processor Study, Contract F30602-76-C-0280, had the overall objective of ascertaining the capabilities and limitations of CCD's to signal processors for long range satellite detection radar systems. A radar system concept was developed which used a two step detection process. Initial detection with coarse range and doppler was determined on the first step with high resolution range and doppler estimates being made on the second step. The radar system was used to develop alternative CCD signal processor concepts from which a baseline, or preferred approach was selected. These results are given in Section 3.0 of the report.

In the initial phases of the program it was apparent that a determination of the state-of-the-art of CCD technology was necessary for identification of realizable CCD parameters in specific applications. The results of this study together with internal RCA measurements were used to characterize CCD operating parameters which are discussed in Section 4.0. A detailed computer simulation of CCD operation described in Section 5.0 was then constructed which included all of the CCD noise sources in addition to the basic charge transfer process. The CCD device was used as the building block for the synthesis of more complex CCD structures such as on delay lines, storage registers and transversal filters. The performance limitations of CCD's as a function of operating parameters were then determined by iteration of the computer simulation. The results of the parameter variations are provided in Section 6.0.

All of the program results are brought together in Section 7.0 which summarizes specific application and projected performance of CCD processors.

2.0 PROGRAM SUMMARY

2.1 STUDY GOALS* AND APPROACH

2.1.1 Study Goals

2.1.1.1 Objective

The objective of this study was to determine the capabilities and limitations of Charge-Coupled Devices (CCD's) as components of very long range pulsed radar signal processing systems.

The effort on the program was to be primarily theoretical with the emphasis placed on the analysis and simulation of device and processor characteristics. Specific orientation was to be placed on the processing of waveforms suitable for the very long ranges and Doppler frequencies involved in satellite detection and tracking.

2.1.1.2 Background

To be cost-effective a long range radar system must be highly flexible in terms of power budgeting and waveform selection, among other things. Both of these requirements imply flexible transmitters and sophisticated computer hardware and software. They also imply flexible and/or adaptable signal processing schemes.

Recent studies have indicated that the cost of building new radars with all of the desired capabilities is probably prohibitive. A viable alternative is *to investigate ways and means for updating existing systems. This approach* will provide at least some of the needed capability, at reasonable cost. One way to increase range capability is to improve the transmitter. Another way is to improve receiver and/or signal processing components or subsystems. CCDs appear to have promise in this area.

2.1.1.3 Specific Areas of Study

The investigation of the application of CCDs to signal processing for the long range radar included virtually all of the basic signal processing functions for the extraction of range, velocity and angle information. These include:

- o Components - tapped delay lines, integrators and filters.
- o Functions - adaptive matched filtering, coherent and non-coherent integration, correlation and convolution.
- o CCD System Parameters - signal storage or integration time, signal-to-noise ratio, dynamic range, instantaneous bandwidth, insertion and processing losses, pattern noise and clock noise, stage isolation, waveform flexibility or adaptability, CCD imposed constraints.
- o Cost/Benefits Tradeoffs.

---
* The study goals as given here are contained in the CCD Signal Processor Study statement of work, RADC PR No. A-6-1063, October 22, 1975.

A baseline system specification was provided for the study which is given in Table 17 in Section 3.0.

2.1.2 Study Approach

2.1.2.1 Study Elements

The study effort elements are shown in Figure 1. A review of the long range satellite detection radar requirements was made and converted to alternative signal processing system architectures. These were then broken down to alternative CCD techniques for each functional subsystem such as pulse compression and spectral filtering. Also feeding into this effort was a review of the CCD state-of-the-art and the development of a CCD model for computer simulation. Key elements of the baseline CCD architecture were selected for parametric performance tradeoffs with the CCD simulator, and the results provide system performance levels as a function of the CCD parameters.

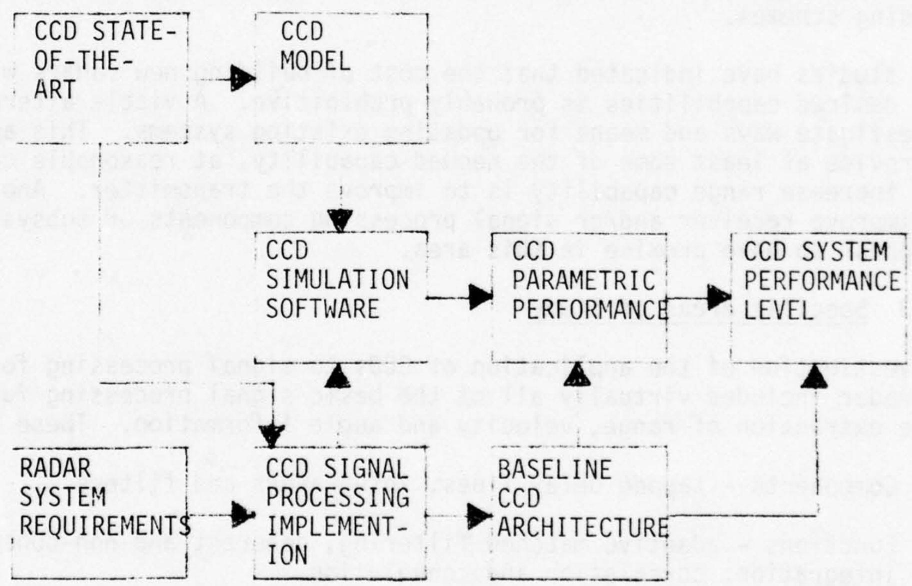


FIGURE 1. CCD SIGNAL PROCESSOR STUDY ELEMENTS

2.1.2.2 General CCD Signal Processing Applications

A broad spectrum of signal processing functions is shown in Figure 2 together with an indication of which ones are felt to be potential CCD signal processing applications. In general, CCD's are suitable for storage functions and those which have fairly high data rates and computational requirements such as most types of filters. Figure 2 shows that the potential applications of CCD's are broad. Most of the given applications involve delay, storage and transversal filtering. These functions are listed in Table 1 with the range of performance parameters which can be encountered in current or developmental radar systems. This parameter range is of course much larger than is required for a long range satellite detection radar. It is, however, useful to consider CCD applications from a broader viewpoint. Many of the requirements which have been derived for the long range radar do not stress the CCD technology. The study has concentrated on the performance of CCD's in the basic functional elements and these results can be applied to other specific applications in addition to the long range radar.

2.2 BASELINE RADAR SIGNAL PROCESSOR

2.2.1 Radar System Parameters

Representative parameters for a long range satellite detection radar are given in Table 2. These parameters were derived from the characteristics of existing long range radars and are thus achievable within todays technology. To maximize detection performance at 25,000 NM, the system losses were reduced by eliminating range and doppler sidelobe weighting on receive and eliminating the CFAR function.

A general radar signal processing system is shown in Figure 3 for the long range radar. A two step detection process was developed for the radar. An uncoded 500 μsec pulse was transmitted on the first step with sixty to eighty pulses integrated. On the second step, a 200 kHz linear FM pulse was employed which increased the range resolution from 40 NM to less than 1.0 NM. One hundred twenty 250 μsec pulses were coherently integrated in this case. These parameters differ somewhat from the baseline radar parameters. The final baseline parameters were revised and the system tradeoffs were completed with the given two-step parameters. Any differences are not significant in the consideration of the application of CCD technology.

2.2.2 Baseline CCD Signal Processor

The signal processing functions implemented in the baseline system included input doppler filtering, corner turning memory, pulse compression (up to 10,000 to 1) and coherent integration. A number of CCD implementations for these systems were considered and the following approaches were selected.

- Input Doppler Filtering - An approach is used which minimizes the number of separate CCD doppler channel filter designs by using a separate demodulating frequency source for each filter.

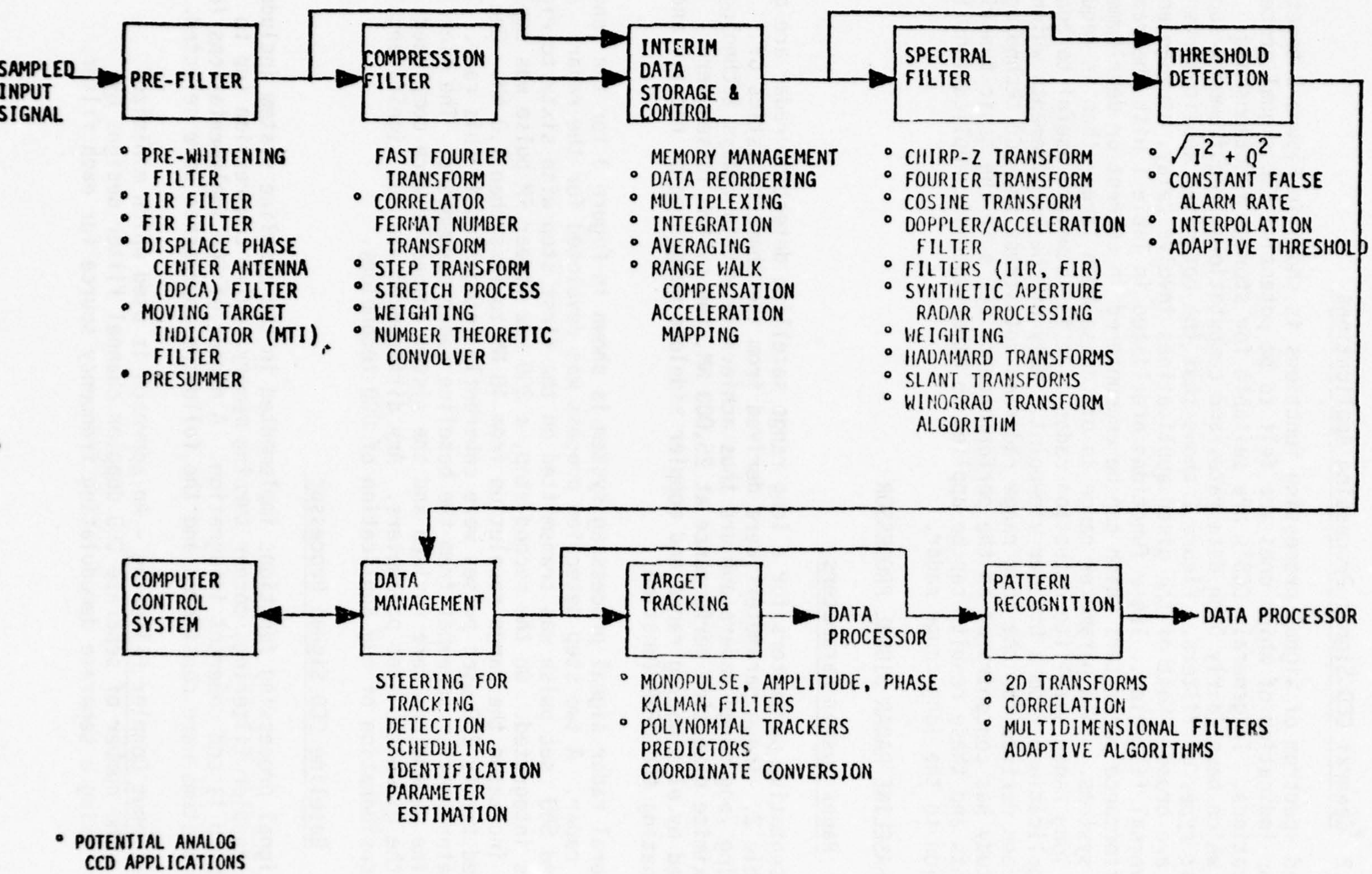


FIGURE 2. GENERALIZED RADAR SIGNAL PROCESSING FUNCTIONS

TABLE 1. PARAMETER RANGES OF SIGNAL PROCESSING FUNCTIONAL ELEMENTS

ELEMENT	SIGNAL PROCESSING FUNCTIONS	CLOCK RATE	NUMBER OF DATA SAMPLES	DYNAMIC RANGE	SPECIAL FEATURES DESIRABLE FOR SOME APPLICATIONS
Delay	Time Alignment and Data Reordering In Most Signal Processing Functions	50 kHz-100 MHz	1-1000	30 - 80 dB	° Programmable Delay ° Data Recirculation
Storage	Data Storage Up To Length of Time Data is in Signal Processor e.g., Target Dwell Time	Load/Unload 50 kHz-100 MHz Store Up to 12 sec.	10-100,000	30 - 80 dB	Random Access
Transversal Filter	FIR Filters, CFAR IIR Filters, Averaging Convolvers, Correlators, Transforms, Interpolation	50 kHz-100 MHz	10-25,000	Input 30 - 60 dB Output 40 - 80 dB	° Programmable Weights ° Internal Reference Store ° Variable Length
Operations	Switching, Arithmetic Functions, Integration	50 kHz-100 MHz	-	30 - 80 dB	

TABLE 2. BASELINE RADAR PARAMETERS

Peak Power:	32 MW
Average Power:	300 kW
Maximum Energy/Pulse:	10000 Joules
Maximum Pulse Length:	500 μsec

RANGE	PULSES INTE-GRATED	TARGET CROSS SECTION	SYSTEM LOSSES	INTE-GRATION TIME	PRF	PULSE LENGTH
3,440 NM Case	7	1.0 m^2	11 dB	.35 Sec	20 Hz	500 μsec
7,000 NM Case	80	1.0 m^2	11 dB	4 Sec	20 Hz	500 μsec
25,000 NM Case	180	12 m^2	7.5 dB	10 Sec	30 Hz	312 μsec

- o Bulk Memory - The length of the CCD memories (up to 36,000 samples) ruled against a serpentine design and dictated an approach which employs input and output multiplexing to moderate length CCD memories. The storage time requirement of 6 seconds or more for these memories is a critical requirement.

- o Pulse Compression - For moderate length pulse compression $\leq$ 500:1, a basic quadrature tapped delay line filter can be used. However, for the alternate wideband requirement of 10,000:1 pulse compression the step transform algorithm was most appropriate.

- o Coherent Integration - The basic simplicity of the CCD transversal filter makes the chirp-Z transform technique preferable for implementing a coherent integration, or spectrum analysis, function.

The baseline subsystem parameters are given in Table 3 while the tradeoff summaries for the input, bulk corner turning memory, pulse compression and coherent integration alternatives are summarized in Tables 4-7.

2.3 CCD CHARACTERISTICS

The CCD physical and electrical characteristics interrelate to determine the performance of the device in a signal processing application. In the analysis and simulation, electrons per CCD storage well have been used as the common measure of CCD performance. That is, the maximum signal level to which all other measures can be normalized is the maximum capacity of a storage well in

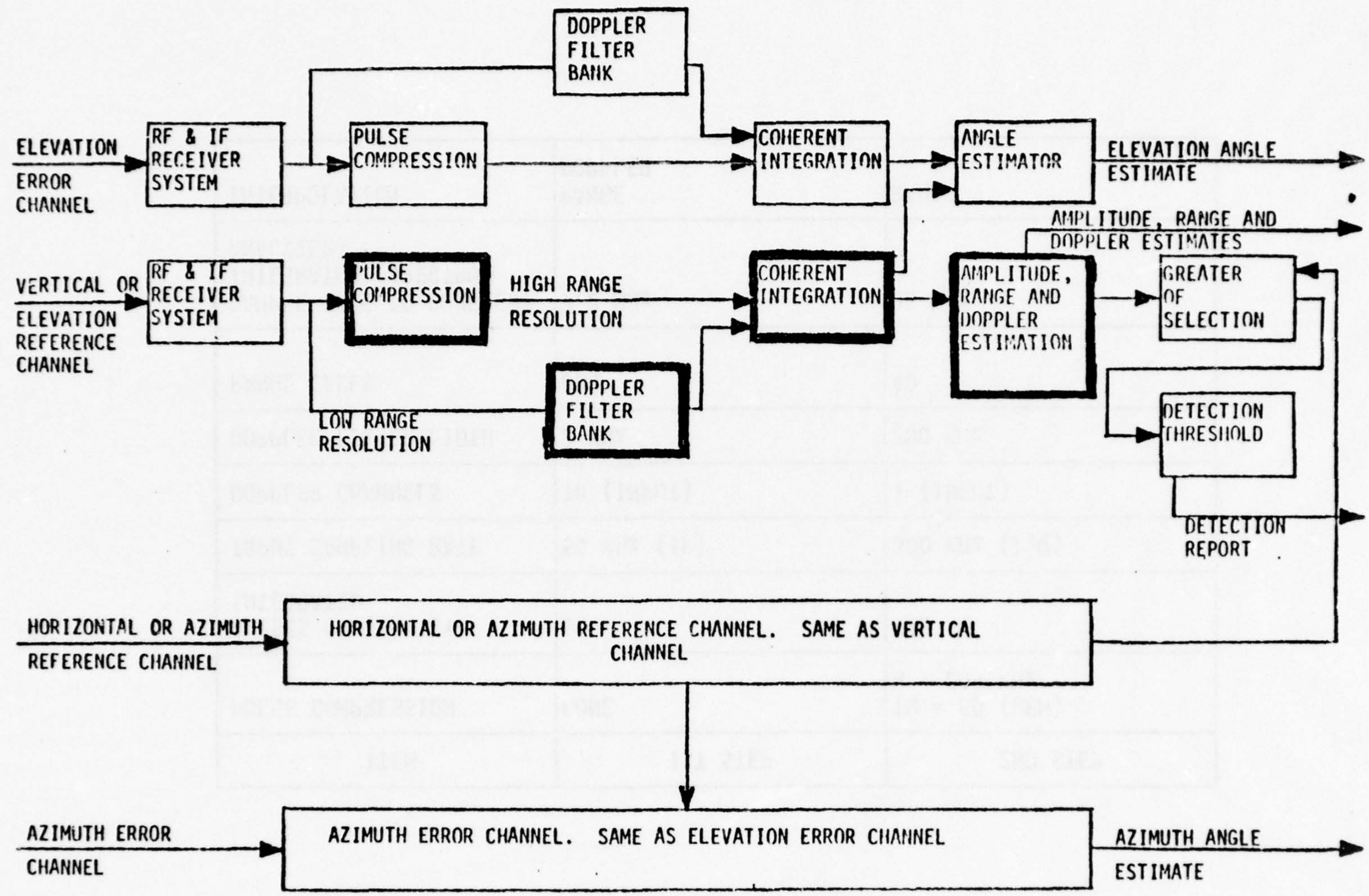


FIGURE 3. RADAR SIGNAL PROCESSING SYSTEM

TABLE 3. BASELINE SUBSYSTEM REQUIREMENTS

ITEM	1ST STEP	2ND STEP
PULSE COMPRESSION	NONE	TW = 50 (LFM) W = 200 KHz
PULSES COHERENTLY INTEGRATED	60	120
INPUT SAMPLING RATE	55 KHz (IF)	300 KHz (I,Q)
DOPPLER CHANNELS	10 (INPUT)	1 (INPUT)
DOPPLER FILTER WIDTH	2 KHz	200 KHz
RANGE CELLS	600	40
SAMPLE RATE TO COHERENT INTEGRATOR (SPECTRUM ANALYZER)	7.2 MHz	96 KHz
INTERPOLATION	RANGE DOPPLER	RANGE

TABLE 4. FIRST STEP INPUT AND DOPPLER FILTERING

	INPUT PROCESS			DOPPLER FILTERS			
TYPE	MAX. VELOCITY FT/SEC	SAMPLE RATE (KHz)	FREQ. SOURCES	TOTAL CCD UNITS	CCD FILTER DESIGNS	NO. OF TAPS	REMARKS
LOW FREQ. IF INPUT	10,000	5.5	1	40	20	28	° SIMPLEST INPUT PROCESSING ° MOST FILTER DESIGNS
	35,000	19.3	1	140	20	97	
FIXED DOPPLER LOW FREQ. IF INPUT	10,000	5.5	10	40	2	28	° MINIMUM FILTER DESIGNS ° REQUIRES FREQUENCY SYNTHESIZER
	35,000	19.3	10	140	2	97	
I/Q DEMODULATION	10,000	26.5	1	40	10	14	° LOWEST SAMPLE RATE ° SMALLEST CCD FILTERS
	35,000	92.8	1	140	10	40	

TABLE 5. BULK MEMORY REQUIREMENTS

CASE		NUMBER OF UNITS	ORGAN-IZATION (FUNCTION)	SAMPLES PER UNIT	TOTAL SAMPLES	MAXIMUM STORAGE TIME	MAXIMUM SAMPLE RATES (KHz)	
							INPUT	OUTPUT
FIRST STEP	MAX VELOCITY =10,000 FT/SEC	40	CORNER TURNING (60x600)	36,000	1.44×10^6	~6 SEC	5.5	7200
	MAX VELOCITY =35,000 FT/SEC	140	CORNER TURNING (60x600)	36,000	5.04×10^6	~6 SEC	19.3	7200
SECOND STEP	200 KHz BW	4	CORNER TURNING 40x120	4,800	19,200	~6 SEC	300	100
	5.0 MHz BW	4	CORNER TURNING 1000x120	120,000	480,000	~6 SEC	7500	2500

TABLE 6. CCD PARAMETERS FOR TW = 10,000 PULSE COMPRESSION ALTERNATIVES

TECHNIQUE	CCD FILTERS		CCD DELAYS		CLOCK RATE	RANGE COVERAGE
	LENGTH	NUMBER	SAMPLES	NUMBER		
STEP TRANSFORM	200	16	2-6000	60	7.4 MHz	FULL RANGE SEARCH
SUB-APERTURE CZT TRANSFORM	1000	192	1000-23,000	46	12 MHz	FULL RANGE SEARCH
	24	192				
SUB-APERTURE CONVOLUTION	1000 (PROGRAM-MABLE)	20	1000-4000	8	6 MHz	44 NM

TABLE 7. COHERENT INTEGRATION ALTERNATIVES

REQUIREMENTS:

INPUT SAMPLE RATE: UP TO 7.2 MHz
APERTURE SIZE: 23, 60, 120 SAMPLES

ALTERNATIVE	CCD LINE LENGTH FOR 120 SAMPLES	CCD CLOCK RATE	SPECIAL CCD REQUIREMENTS
CHIRP-Z FILTER	120 FILTER, 120 DELAY	3 TIMES REAL TIME INPUT RATE	
STORED COEFFICIENT	120	REAL TIME INPUT RATE	° SERIAL-PARALLEL BUFFER ° N x N COEFFICIENT STORAGE MULT. ° ANALOG MULTIPLIER ON CHIP
DELTIC	120	120 TIMES REAL TIME INPUT	LOW TRANSFER LOSS DUE TO RE-CIRCULATION (DELAY ONLY)

electrons. Similarly, noise sources are also given in terms of rms electrons and the maximum dynamic range of a CCD, the peak signal to rms noise, can be calculated by taking the ratio of the well capacity in electrons to the total rms noise electrons. Other factors will act to reduce the operating dynamic range of the CCD. These include charge transfer inefficiency, input sampling non-linearities and dark current. Dark current effects are especially important in applications which require charge to be stored for extended periods of time in a CCD or moved slowly through a CCD.

2.3.1 Signal Sample Storage

The storage capacity of a CCD is proportional to gate area and clock voltage. This parameter, which determines the maximum signal dynamic range, varies from 10^5 to 10^8 electrons for typical gate areas and clock voltages.

2.3.2 Transfer Inefficiency

The small percentage of charge which is left behind with each charge transfer sets the CTI or charge transfer inefficiency level. This varies in the general range from 3×10^{-4} to 2×10^{-5} with the buried channel CCD's (BCCD) performing somewhat better than surface channel CCD's (SCCD).

2.3.3 CCD Noise Sources

Table 8 lists typical values of rms electrons for the CCD noise sources identified as being significant in CCD operation.

TABLE 8. TYPICAL VALUES FOR CCD NOISE SOURCES

	RMS ELECTRONS
o TRANSFER NOISE (αCTI)	SCCD ~ 100 BCCD ~ 20
o THERMAL SHOT NOISE	1 - 13
o TRAP NOISE (α TEMPERATURE AND AREA)	~ 50
o INPUT NOISE (α TEMPERATURE AND INPUT TECHNIQUE)	~ 35
o OUTPUT NOISE (α TEMPERATURE, BANDWIDTH)	100 - 200

2.3.4 Dark Current

The dark current is primarily dependent on temperature and accumulates in a given well to reduce well capacity. A typical well will fill due to dark current in about 10 seconds at 25°C to 50°C.

2.3.5 CCD Input Sampling

The sampling aperture requirements are not firmly established. If the CCD input sampling structure acts as a true averager over the aperture time, the aperture width can be larger than if a random noise is introduced as is

assumed for A/D converter operation. The input structure is the main source of non-linearity in CCD's and can limit the dynamic range to as much as 20 dB less than a full well.

2.3.6 Dynamic Range

Using the definition of dynamic range as the ratio of peak signal to rms noise, the dynamic range of a typical CCD delay line is about 65 dB. Dynamic range will depend on temperature, bandwidth and clock rate.

2.3.7 Signal Isolation Between Cells

Signal isolation between cells is controlled by potential charge barriers used in the physical construction of the CCD and is generally not a problem.

2.3.8 CCD Summary Characteristics

Table 9 summarized CCD characteristics which have been achieved with CCD devices.

TABLE 9. SUMMARY OF REPORTED CCD CHARACTERISTICS

o Maximum Number of Stages	910
o Minimum Transfer Inefficiency	$1 * 10^{-5}$
o Maximum Sample Rate	180 MHz
o Minimum Dark Current Density	$1.5 \frac{nA}{CM^2}$ @ 25°C
o Maximum Dynamic Range	75 dB
o Minimum Harmonic Distortion	-45 dB

2.4 CCD SIMULATION

The CCD simulation was written in FORTRAN IV using a modular programming structure for a PDP-11/40. The CCD noise, dark current and CTI are introduced as the electron packets are transferred from one potential well to the next. The CCD noise sources were modeled as Gaussian noise with non-standard variances. The dark current electrons are added to each potential well as an average with a Rayleigh distribution. The CCD functions which were modeled are a delay line, tapped delay line filter, storage register and linear FM matched filter. Table 10 summarizes the noise parameters used in the simulation.

The CCD's were varied in their operation as a function of clock rate, temperature, CTI, tap weight error and number of stages.

TABLE 10. CCD SIMULATION NOISE SOURCES

NOISE SOURCE	MEAN	VARIANCE	DISTRIBUTION
Input/Output	0	$2K_3\ K\ T\ C_i/q^2$	Gaussian
Shot	0	$J_D\ A\ K_2/q\ f_c$	Gaussian
Trap	0	$.7\ K\ T\ N_{SS}\ A$	Gaussian
Filter Tap Weights	Weight Value	$(\text{Percent Error})^2$	Gaussian
Transfer	0	$2\ e\ N_S$	Gaussian
Dark Current*	$J=J_{gd}+J_{gn}+J_{gs}$	$J^2/(\pi/2)$	Rayleigh (J_{gs} term only)

* See Section 4.5 for expanded equation.

2.5 CCD SIMULATION

2.5.1 General Conclusions

Specific device characterization results are given in Section 4.0 and simulation results are provided in Section 6.0 and excerpted in Section 7.0. General conclusions of the program include the following points.

- o The performance capability of CCD devices provides usable dynamic ranges of from 50 to 70 dB which is satisfactory for most applications.
- o The clock rate capability of up to 10 MHz for surface channel CCD's and over 100 MHz for buried channel CCD's provides wide application potential.
- o The storage time of CCD's should be held to less than 1 second unless cooling is used and can be extended well beyond 10 seconds if the temperature is held to less than 0°C.
- o The simulation program revealed unique results relative to CCD performance in the presence of dark current. In the operation of a linear FM matched filter, the dark current build-up creates an output dynamic range floor which first encompasses the region outside the matched filter response followed by the sidelobes and finally envelopes the main-lobe as the dark current increases.

- o Charge transfer inefficiency (CTI) will be stable and at levels which do not degrade performance over the full clock rate of CCD devices provided that the control and clock levels are properly maintained. In the event that the CCD is operated at a high CTI, the bandwidth capability is reduced and amplitude dispersion of signals will result.

- o Programmability is a desirable feature to be incorporated in CCD's because it eliminates chip design costs for special applications and can permit signal processor parameter variations.

- o A digital microprocessor rather than a CCD is most appropriate for the post detection processing functions which do not include delay and storage and which do not operate with a 100% signal sample duty factor.

- o The external control and amplification circuitry in a CCD system in large measure limits the CCD performance and application. The development of on-chip controls is therefore of primary importance and should be included in any new CCD chip developments.

2.5.2 CCD Programmability

Table 11 lists the CCD programmability functions, the means for achieving them and the status of the technology. The most important feature is the achievement of electrically programmable weights which can be held for an extended length of time (seconds). Industry effort is being concentrated on this area and some success has been reported.

2.5.3 CCD Bandwidth Limitations

There is both a high and low frequency bandwidth limitation of CCD's. At the high end they are limited by the clock rate at which the devices can be operated. A useful rule of thumb is that surface channel CCD's can be operated at clock frequencies up to about 10 MHz while buried channel or peristaltic CCD's have usable clock frequencies beyond 100 MHz. No discernible frequency dependent degradation in performance has been measured below the maximum clock frequencies.

The low operating frequencies of CCD's are limited by dark current which increases with temperature. Assuming dark current filling 20% of the well as being the limiting threshold the maximum storage time versus temperature is given in Table 12.

Another important factor in the operation of CCD's at high frequencies is the design of the peripheral circuits and packaging. The practical application of CCD's is probably limited more by these problems at very high frequencies than by basic device capability.

TABLE 11. CCD PROGRAMMABILITY CONSIDERATIONS

TECHNIQUE CATEGORY	TECHNIQUES	TECHNOLOGY STATUS
Electrically Variable Weights	° Floating Gate Taps ° Integrated Multipliers ° Analog Storage	° Storage Time is Limited ° Multiplier is Problem ° Floating Gate Taps are Developed
Semi-Programmable Weights	(a) Split Gate Weighting (b) Electrically Programmed Permanent Weights	(a) Established But Not Truly Programmable (b) Technique Not Developed
Switching and Shifting Charge	Use of Transfer Gates and Barrier Controls	° Developed for Binary Signals ° Analog Technology Not Established
Variable Length	° Setting Weights to Zero ° Control Length by Switching	Requires Switching or Programmable Weights
Function Select	° Reconfiguration of Chip	Requires Extensive Development
Digital Logic Approach	Basic Digital Gate Functions Implemented with CCD Controls	° May be in Laboratory Stage ° Suitable for Pipelined Functions such as Digital Filters and FFT's

TABLE 12. LOW FREQUENCY LIMITATIONS OF CCD DELAY LINES (DARK CURRENT FILLING 20% OF WELL)

TEMPERATURE	MAX STORAGE TIME (SECONDS)
- 55°C	>12 Seconds
- 25°C	>12 Seconds
+ 5°C	>12 Seconds
+ 35°C	6 Seconds
+ 65°C	0.75 Seconds
+ 95°C	< 0.1875 Seconds
+125°C	< 0.1875 Seconds

2.5.4 Post Processing Functions

The post processing functions in a radar signal processor generally refer to those following the basic matched filtering operation. Doppler processing is generally considered with the pulse compression system since it forms a matched filter for a target with a specific doppler. Post processing functions include: thresholding, range and angle estimation, bulk filtering, constant false alarm rate (CFAR) processing, interpolation, predictors and various pattern recognition procedures. Many of the functions are identified in Figure 2. The application of CCD's is possible in those cases where the computations can be pipelined. Implementation of many post processing functions with CCD's is even more dependent on achieving programmability and adaptability than the pre-post processor functions. An important consideration relative to the appropriateness of CCD processing is the processing rate requirements of specific functions and whether digital microprocessor based techniques will ultimately be the best approach.

Table 13 summarizes the principle post processing functions and rates CCD's and microprocessors as to the most appropriate implementation.

2.5.5 On-Chip CCD Controls

The feasibility of incorporating on-chip clocking and controls to CCD devices has been demonstrated. This technology step is a key to the practical implementation of CCD's in many applications. It is expected that development of on-chip peripheral circuitry will continue and lead to CCD's with stable performance characteristics which will permit their application in the field. An important facet of this is CCD replaceability. CCD performance must be characterized and predictable to permit field replacement without readjustment of the operating timing or control values.

2.5.6 Sub-System Performance Levels

The expected performance levels of the key CCD elements; delay lines, memories, and transversal filters is summarized in Tables 14 - 16. These results are based upon measurements, the published literature and the simulation. The simulation results in Section 6 provide a large number of specific cases demonstrating the operation of the CCD functions. In the

TABLE 13. POST PROCESSOR CCD CANDIDATES

POST PROCESSING FUNCTION	COMPUTATION RATE	DUTY CYCLE	PRINCIPAL PROCESSING ELEMENTS (ARCHITECTURE)	REMARKS RE CCD IMPLEMENTATION	ADVANTAGE TO	
					CCD	MICRO-PROCESSOR
Threshold Detection	Video Sample Rate	100%	Amplitude Comparison	Peripheral CCD, Analog Circuitry	X	
Normal Threshold Computation	<< Sample Rate	~ 1%	Weighting & Adding Several Sensor Inputs	Requires Programmability		X
Interpolation	Sample Rate or Greater	100%	Transversal Filter	Programmability of Weights is Desirable	X	
CFAR	Sample Rate or Greater	100%	Transversal Filter	Programmable Weights for Adaptive CFAR	X	
Range & Angle Estimation	<< Sample Rate	< 1%	Add,Subtract,Mult., Divide,Small Delays	Specialized Analog Functional Would Do Mult. & Divide Operation		X
Pattern Recognition (Correlation, 2D Transform)	High	< 1%	Programmable Transversal Filter for 2D Transform	Computation Rates Are High Since Waveforms are Wideband	X	
Predictors, Coordinate Conversion, Kalman Filters	<< Sample Rate	Small	General Arithmetic Operations	Required Wide Programmability		X

TABLE 14. EXPECTED CCD DELAY LINE PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE	95 dB	512 STAGES (CASE A) S_R = 100 kHz, T = +5°C INPUT LINEAR TO FULL WELL
	70 dB	512 STAGES S_R = 1000 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
	50 dB	512 STAGES S_R = 100 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
NOISE FIGURE	1.5 dB	DELAY LINE (CASE A)
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INPUT/OUTPUT STRUCTURES
LINEARITY (HARMONIC DISTORTION)	-45 dB	TYPICAL LEVEL WITH STANDARD INPUT TECHNIQUE (MEASURED RESULTS)

TABLE 15. EXPECTED CCD STORAGE REGISTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE*	45 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, RE FULL WELL
	18 dB	STORAGE TIME = 12 SEC TEMPERATURE = 35°C, RE FULL WELL
	65 dB	STORAGE TIME = 1 SEC TEMPERATURE = 5°C, RE FULL WELL
	25 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, -20 dB RE FULL WELL
INSERTION LOSS LINEARITY	SAME AS DELAY LINE CASE	

* THE DYNAMIC RANGE FOR CCD'S IN A STORAGE MODE IS LOW BECAUSE OF THE BUILD-UP OF DARK CURRENT VARIATIONS WHICH ARE AVERAGED OUT IN THE DELAY LINE CASE.

TABLE 16. EXPECTED CCD TRANSVERSAL FILTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC*	MEASURE	CONDITIONS	
MAX SIDELOBE LEVEL (IDEAL = -39.6, TW PRODUCT = 65)	-39.5 dB	TAP ERRORS = 1%	T = 5°C CLOCK RATE (f_s) = 10^5 Hz
	-39.3 dB	TAP ERRORS = 3%	
	-35.6 dB	TAP ERRORS = 10%	
	-36 dB	f_s = 10 kHz TEMP. = 95°C	ZERO TAP WEIGHT ERRORS
	-38.5 dB	f_s = 10 kHz TEMP. = 65°C	
DYNAMIC RANGE (OUTPUT) CCD FILTER = 129 STAGES, TW = 65	80 dB	f_s = 100 Hz TEMP. = -25°C	RE FULL WELL
	60 dB	f_s = 100 Hz TEMP. = 5°C	
	60 dB	f_s = 300,000 Hz TEMP. = 65°C	
	110 dB	f_s = 3000 Hz TEMP. = -25°C	
INSERTION LOSS	UP TO 26 dB	INPUT/OUTPUT STRUCTURES	
LINEARITY (HARMONIC DISTORTION) CCD FILTER = 129 STAGES, TW = 65	-63 dB	RE OUTPUT	
	-45 dB	RE INPUT	

* THESE MEASUREMENTS APPLY TO CORRELATORS, CONVOLVERS, MATCHED FILTERS AND CZT SPECTRUM ANALYZERS IN SO FAR AS FUNDAMENTAL CCD IMPOSED LIMITATIONS.

examples in Section 6.0 examples were generally chosen which show performance variation with a parameter such as temperature. Thus many examples involve low clock rates and high temperatures which begin to show adverse CCD performance. Many, if not most, applications of CCD's will not see these problems simply because dark current will not be significant.

Noise figure will depend upon the application of the CCD. We can consider the delay line case for an example. The factor kTB yields an output voltage level into a 1000 ohm resistance of about 6.3×10^{-7} volts for a bandwidth of 100 kHz. A CCD peak output voltage with a full well measured at the drain of 0.05 volts gives a maximum dynamic range of 98 dB relative to thermal noise or about 92 dB relative to receiver noise. Thus the effective CCD noise figure is about 1.5 dB in this case since the delay line CCD self noise is -95 dB relative to a full well. On the other hand in those applications such as the storage mode the operating dynamic range of the CCD is severely reduced due to dark current build-up. Thus the noise figure is increased accordingly. In these applications, the operating range of the system would be set to minimize system losses while operating over the dynamic range. Setting the receiver system noise 10 dB below the CCD noise level gives an effective noise figure of 0.3 dB. In the CCD operation, generally the CCD self noise is greater than the thermal noise level.

2.5.7 CCD Cost/Performance Tradeoffs

General projections on CCD system costs relative to other technologies can be made, but specific tradeoffs will depend on the application and the competing technology. For low data rate applications, microprocessor techniques will prevail as most cost-effective. As the data rates and processing requirements increase to the hundreds of kilohertz up to 10 MHz, CCD's will find increasing application. Buried channel CCD's operate up to and beyond 100 MHz. Figure 4 indicates general speed performance categories for various technologies. The line of demarcation between different approaches will fluctuate depending on the specific application. Note that every category of processor can be built with special purpose digital hardware. This involves paralleling at the very high rates.

Costs can be expected to follow the basic pattern of Figure 5. A standard implementation using MSI digital technology will be relatively low in cost but as the number of units to be constructed increases, the parts cost will become dominant. Thus initial investments in either LSI or CCD development will produce substantial savings in the end. Since fewer chip designs are required for CCD's and fewer parts will be required in the system, the CCD unit costs will be lowest for large volumes. The crossovers of "break-even" costs indicated in Figure 5 can not be assumed to hold in general. Each application will produce a different tradeoff.

2.6 RECOMMENDATIONS

2.6.1 Device Developments

On a device level programmable features should be emphasized. A need exists for improvement of the linearity of the input sampling structure. CCD clocking, control and amplification functions should be incorporated on the

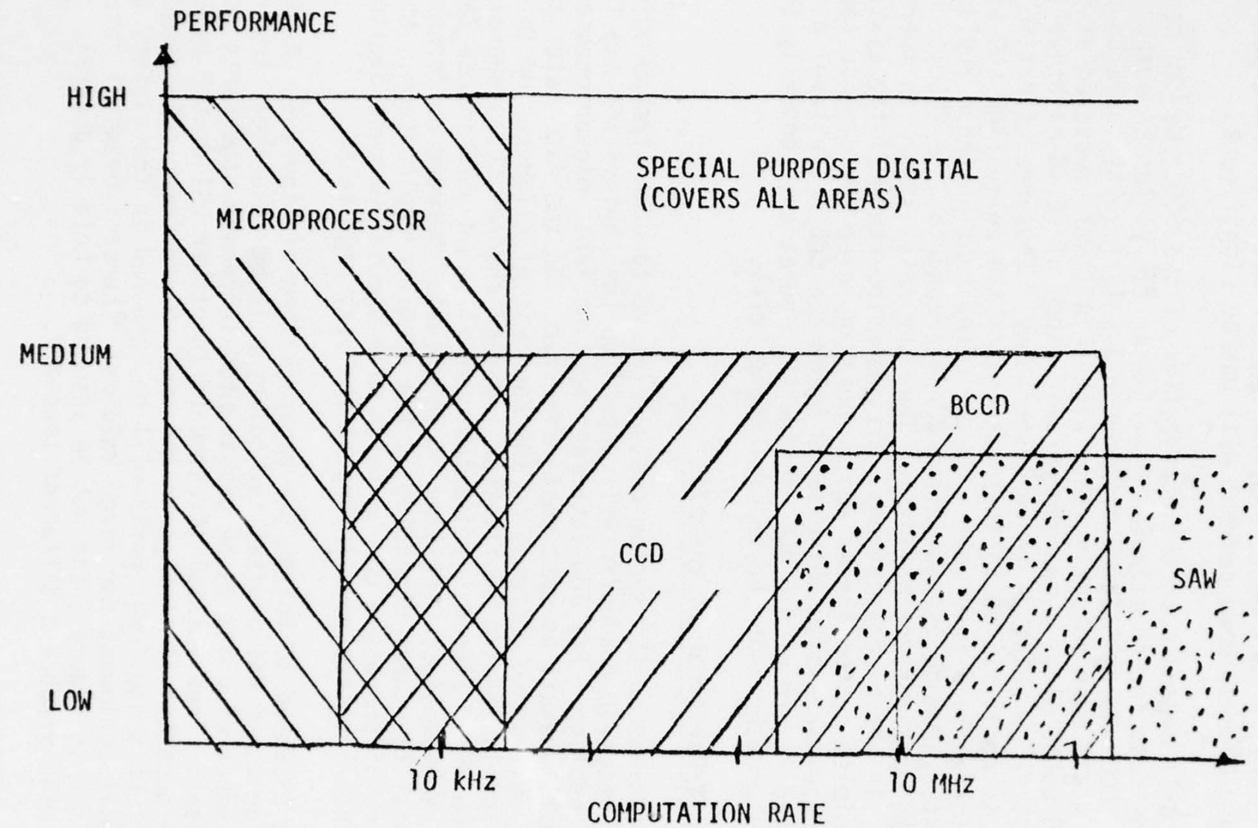


FIGURE 4. TECHNOLOGY CATEGORIES

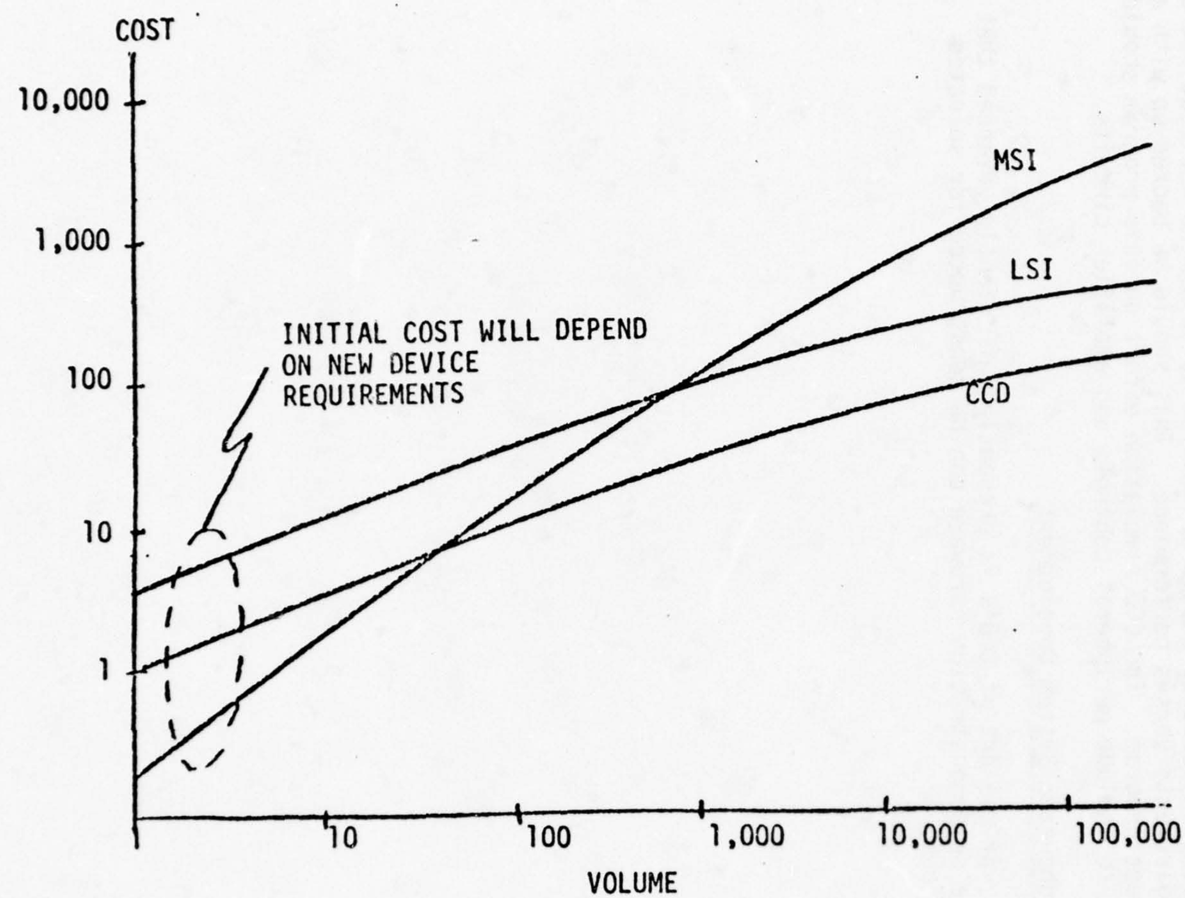


FIGURE 5. TECHNOLOGY COST TRENDS

CCD chip. Tests are necessary to more completely characterize CCD's in terms of reliability and temperature stability.

2.6.2 Analysis

The CCD sampling process should be studied to determine the required aperture time requirements versus performance. This should be backed up with a measurement program. The CCD simulation effort on this program should be extended to include peripheral controls and amplifier circuits.

2.6.3 Subsystem-System Development

The state-of-the-art of CCD's is presently sufficiently advanced that prototype or demonstration hardware can be constructed for selected applications.

3.0 RADAR SYSTEM AND SIGNAL PROCESSING REQUIREMENTS

The stated objective of this program has been to determine the major capabilities and limitations of CCD's as components in very long range pulsed radar signal processors. This objective has served as a base from which the application of CCD's to a broad range of signal processing functions can be derived. It will be shown in this section that possible signal processor subsystems for the long range radar applications comprise a representative set of the subsystems of general interest for wider applications.

3.1 RADAR PARAMETERS

3.1.1 Long Range Radar System Requirements

The contract Statement of Work lists a set of radar characteristics for meeting long range satellite detection requirements. These are listed in Table 17. The bounds on key radar parameters of several long range radars currently in use is listed in Table 18.

TABLE 17. LONG RANGE RADAR REQUIREMENTS

Target Altitude	100 NM to 25,000 NM
Target Radial Velocity	± 10,000 ft/sec to ± 35,000 ft/sec for Elliptical Orbits
Transmission Frequency	435 MHz
Target Cross Section	1.0 Sq. Meter @ 435 MHz
Probability of Detection	50% to 90% @ 3440 NM 50% @ 7000 NM, Max. Range 25,000 NM
Range Resolution	1 NM for Two Targets with Up to 10 dB Differential Amplitude
Velocity Resolution	< ± 50 ft/sec
Angular Accuracy	± 1/10 Beamwidth
False Alarm Probability	10^{-6} (Assumed)

TABLE 18. RADAR* PARAMETER BOUNDS

Peak Power	1.2 MW to 32 MW
Average Power	25 KW to 300 KW
Transmitted Energy Per Pulse	2400 to 10000 Joules
Transmission Frequency	Around 435 MHz One of the Systems at 1300 MHz
PRF	20 to 30 PPS
Pulse Lengths (Coded)	250 μsec to 2000 μsec
Waveform Bandwidths	500 Hz to 5 MHz
Range Resolution	200 Feet to ± 1 NM

The foregoing radar requirements and radar parameter bounds can be combined by use of the radar equation to define a baseline satellite detection radar. The radar range equation can be expressed for the signal-to-noise ratio (S/N) of a single pulse.

---

* Based on FPS-17, FPS-49, FPS-79, FPS-80, FPS-85 and Cobra Dane.

$$S/N = \frac{P_t \tau G_T G_R \lambda^2 \sigma_t (1.07)}{\overline{NF} R^4 L}$$

The equation is diagrammed in Table 19 to derive a set of appropriate radar parameters. The table indicates that a 1.0 square meter target has a S/N of 4.71 dB for a single transmitted pulse 500 μsec in length using a peak power of 20 MW and antenna gains of about 42 dB. The S/N required for P_d = 90% and $P_{fa} = 10^{-6}$ is about 13 dB. Thus the coherent integration of 7 pulses is required to meet the 3440 NM range requirement.

At 7000 NM the single pulse S/N is -7.69 dB. To achieve a Pd of 0.5 with a false alarm probability of 10^{-6} requires a S/N of 11.2 dB. Thus a S/N enhancement of 18.83 dB is required, or the integration of 78 pulses. An integration time of about 4 seconds provides the 78 pulses. The losses used in the range equation are estimated, and probably on the high side. Thus the 4 seconds of integration time specified is more than adequate for the 7000 NM detection range and 1 square meter target.

To reach a range of 25,000 NM requires 20.06 dB more gain than the 7000 NM case. The duty factor for the 20 Hz PRF and a pulse length of 500 μsec is 100 to 1. Thus a peak power of 32 MW matches the 300 kW average power limitation. However, the energy per pulse in this case is 16,000 joules, or more than the 10,000 limit of the bounds in Table 18. In order to stay within the average power limitation of 300 kW and the maximum energy per pulse of 10,000 joules with a 32 MW peak power, the pulse length must be 312 μsec and the PRF increased to 30 Hz. The only variables left are the target size, losses and the number of pulses integrated unless the basic radar parameters are improved. The loss budget in the long range search mode can be altered in the signal processor. In the 11 dB total loss budget 1.3 dB is typically due to matched filter weighting, 1.6 dB may be due to doppler (coherent integrator) filter weighting and 0.6 dB may be due to a CFAR function loss. All of these losses totalling 3.5 dB can be eliminated in a mode change if the radar has sufficient programmability. If a limit of 10 seconds of integration time is placed on the system due in part to dark current build up in a CCD storage or integration device the maximum number of pulses per dwell at a PRF of 30 is 300. This represents a signal integration improvement over the 78 lower power longer pulses used in the 7000 NM mode of 5.8 dB. Under the foregoing assumptions, the baseline radar can detect a target with a cross section of 20.06 - (3.5 + 5.8) = 10.76 dB or 11.9 m^2.

In summary, the baseline radar parameters for the system incorporates the radar parameter bounds of Table 18. The overall baseline parameters meeting the minimum performance goals at 3440 NM and 7000 NM are summarized in Table 20.

3.1.2 Radar System Considerations

The baseline CCD signal processor will be used for long range satellite detection and tracking radar applications. A basic characteristic of these radars is a very low PRF along with very high pulse energy. The satellites of interest are often non-cooperative and in non-powered flight. Thus the satellite path will follow predictable orbits.

A signal processor configuration for these satellite radars will have

TABLE 19. RANGE EQUATION TABULATION

PARAMETER	EQUATION SYMBOL	VALUE	(+) dB	(-) dB	OUTPUT S/N dB
Transmit Power (Watts)	P_t	A,B: $20x10^6$ C: $32x10^6$	73.01 75.05		
Antenna Gain (Transmit)	G_T	-	42.10		
Antenna Gain (Receive)	G_R	-	41.70		
Wave-length (cm)	λ^2	69	36.77		
Target Cross Section (m^2)	σ_t	1.0	0		
System Noise Factor	$\overline{NF}_0$	2.37		3.75	
Pulse Length (Sec)	τ	A,B: $500x10^{-6}$ C:$312x10^{-6}$		33.01 35.05	
Range (NM)	R	A: 3440 B: 7000 C: 25000		A: 141.4 B: 153.8 C: 175.9	
Losses	L			11	
Constant		1.07	0.29		
		TOTALS	195.91	A: 189.16 B: 201.56 C: 223.66	4.71 -7.69 -27.75

TABLE 20. BASELINE RADAR PARAMETERS

Peak Power:	32 MW
Average Power:	300 kW
Maximum Energy/Pulse:	10000 Joules
Maximum Pulse Length:	500 μsec

RANGE	PULSES INTEGRATED	TARGET CROSS SECTION	SYSTEM LOSSES	INTEGRATION TIME	PRF	PULSE LENGTH
3,440 NM Case	7	1.0 m^2	11 dB	.35 Sec	20 Hz	500 μsec
7,000 NM Case	80	1.0 m^2	11 dB	4 Sec	20 Hz	500 μsec
25,000 NM Case	300	12 m^2	7.5dB	10 Sec	30 Hz	312 μsec

constraints imposed by the satellite environment. These constraints include:

1. Satellite Orbits
2. Satellite Velocity Limits
3. Radar Power Limits
4. Range Resolution Requirements

3.1.2.1 Satellite Orbits - Satellites in non-powered flight follow an orbit that is a conic section with one focus at the earth's center. A simplified derivation of the equations of motion developed by C. S. Lerch [1] will be used. Figure 6 shows a typical orbit and gives the applicable equations of motion of this orbit. It can be shown that the maximum range rate at the radar occurs when the radar is in the plane of the orbit and when θ is plus or minus 90°. It follows that:

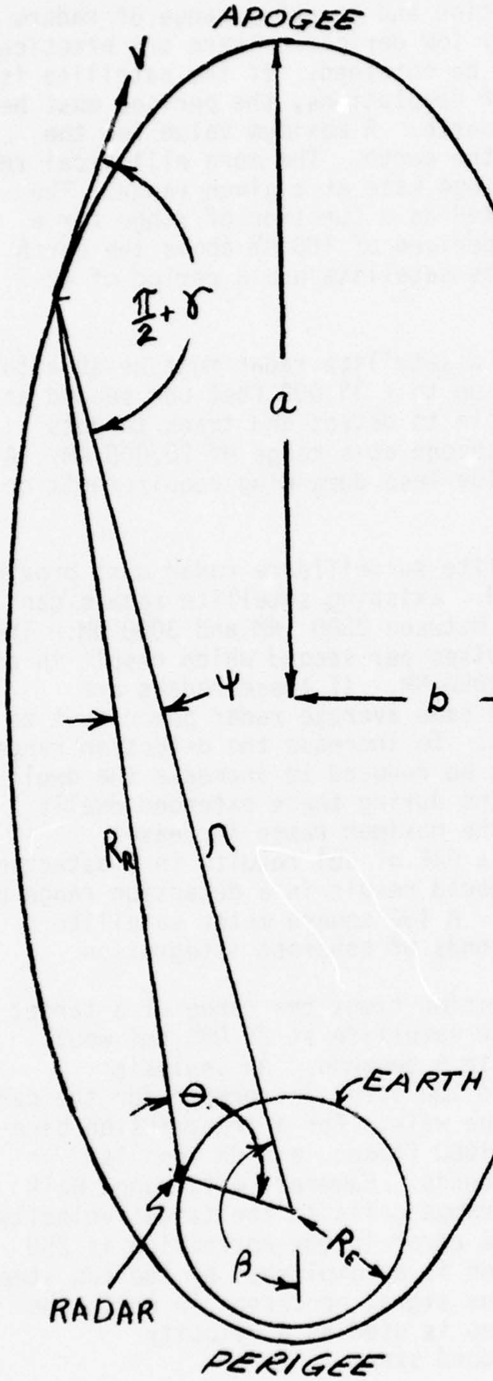
$$R_R = \sqrt{\Omega^2 - R_E^2}$$

$$\sin \psi = R_E/\Omega$$

The maximum range rate (V_{RM}) at the radar is:

$$V_{RM} = V_{COS}\left(\frac{\pi}{2} + \gamma + \psi\right) = -V_{SIN}(\gamma + \psi)$$

3.1.2.2 Satellite Velocity Limits - Satellites can have very elliptical orbits particularly if the prevention of detection of the satellite is of



EQUATIONS OF MOTION

$$e = 1 - \left(\frac{b}{a}\right)^2$$

$$V^2 = 62740\left(\frac{2}{r} - \frac{1}{a}\right)$$

$$r = a\,\frac{(1-e)^2}{1+e\cos\beta}$$

$$\tan\gamma = \frac{e\sin\beta}{1+e\cos\beta}$$

$$\frac{d\beta}{dt} = \frac{62740\, a^{\frac{3}{2}}(1+e\cos\beta)^2}{b^2}$$

FIGURE 6. SATELLITE ORBIT

primary concern. Thus a satellite that is to elude detection could have an apogee that is well beyond the skin detection and tracking range of radars and would speed past the earth with a very low perigee. There are practical limits to the apogee and perigee that can be obtained. If the satellite is to maintain an orbit for a large number of revolutions, the perigee must be at least 100 NM above the surface of the earth. A maximum value for the apogee seems to be about 60,000 NM above the earth. The more elliptical the satellite orbit, the higher will be the range rate at a given range. The maximum range rate at the radar was computed as a function of range for a satellite with an apogee 60,000 NM and a perigee of 100 NM above the earth. These results are shown in Figure 7. This satellite has a period of 42.7 hours.

To meet this worst case elliptical orbit, a satellite radar must be able to detect and track targets with range rates up to ± 35,000 feet per second at short ranges (100 NM). It must also be able to detect and track targets with range rates up to ± 10,000 feet per second at a range of 25,000 NM. A less eccentric orbit would obviously provide less demanding requirements on the radar.

3.1.2.3 Radar Power Management - A satellite surveillance radar must provide detection of targets from 100 to 25,000 NM. Existing satellite radars can detect one square meter targets at ranges between 2500 NM and 3000 NM. These radars use PRF values between 20 and 30 pulses per second which result in an unambiguous range coverage of 2700 NM to 4050 NM. If these radars are modified using a CCD signal processor, the same average radar power must be used to provide detection at longer ranges. To increase the detection range of a fixed power radar, the scan rate must be reduced to increase the dwell time at a given angle position. The returns during these extended dwells must be coherently integrated to provide the maximum range increase. Coherent integration over six seconds (at a PRF of 30) results in a detection range increase of up to 3.31 to 1. This would result in a detection range of about 7000 NM for a 1 square meter target. A 100 square meter satellite could be detected at 25,000 NM using 6 seconds of coherent integration.

3.1.2.4 Range Walk - For very long integration times the range of a target may move from one range cell to another. A satellite at 25,000 nmi would move up to ± 50,000 feet or about ± 10 NM in 6 seconds. An analysis was made of the loss in S/N with respect to the ideal integrator for the case in which no correction is made for the range walk. For a transmission bandwidth of 200 khz and a target velocity of 1000 ft/sec. a 3 dB loss is incurred for an integration time of .68 seconds. However, with range walk correction, (matching the movement of the range cells to the target velocity) a loss of less than .5 dB will occur if the error in the correction is 250 feet/sec or less. The range walk correction is accomplished by the two step detection process described for the baseline signal processor in which the doppler frequency obtained on the first step is used as a velocity correction on the high range resolution second step.

3.1.2.5 Ionospheric Dispersion - Refraction of UHF frequencies through the ionosphere are frequency dependent and vary as a function of time. For wideband waveforms the effect is akin to passing the signal through a filter

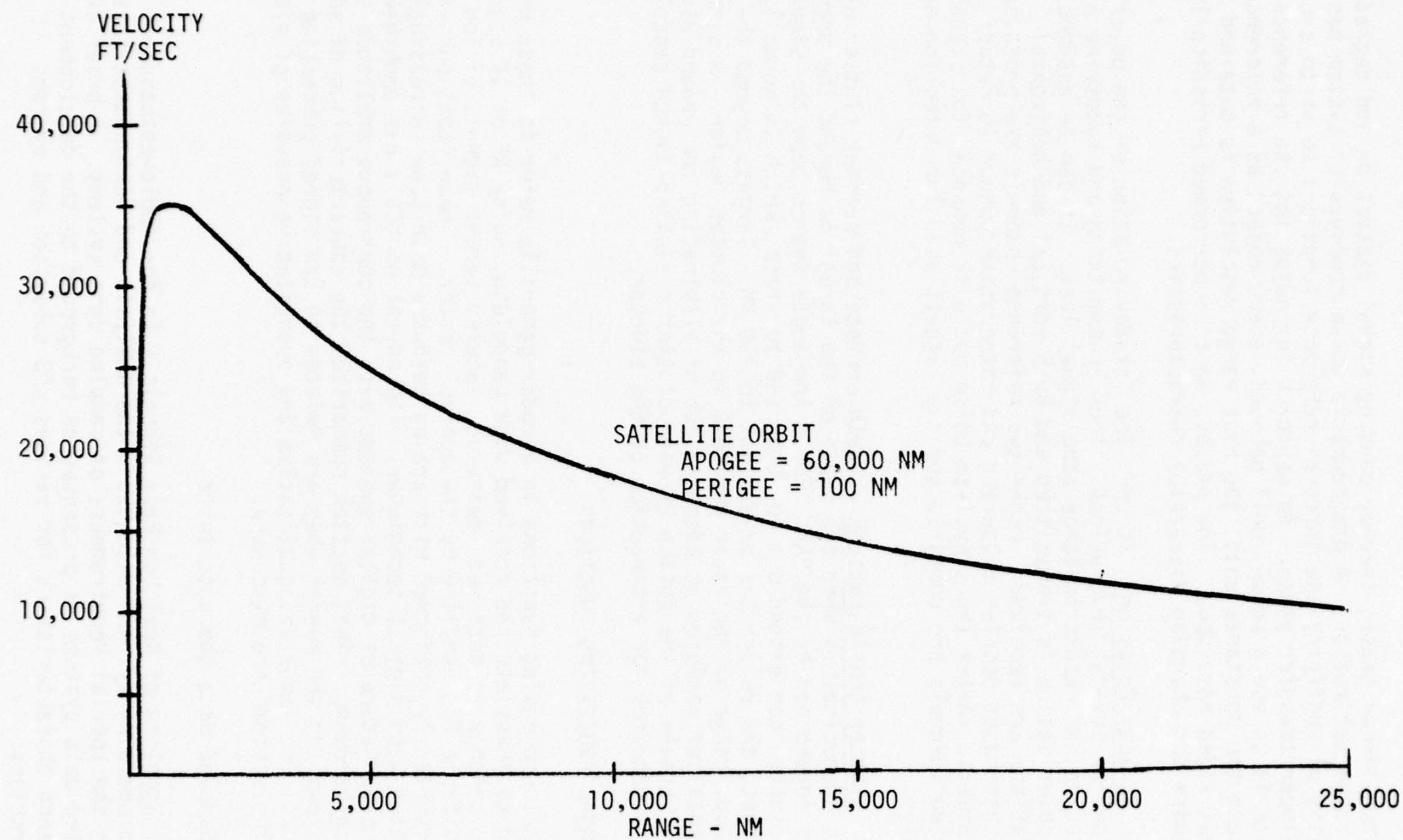


FIGURE 7. MAXIMUM VELOCITY PROFILE FOR A SATELLITE

with a non-linear phase, thereby causing signal distortion and degradation of the range estimation. A programmable pulse compression system has the capability of modifying the internal reference functions so as to synthesize a non-linear transfer phase. An approach for adjusting the reference function constants is to use a known, well behaved, space object as a reference, and manipulate the constants until the best range resolution is obtained (the narrowest video envelope). The process must be performed periodically to accommodate the changing dispersion characteristics.

3.1.2.6 Faraday Rotation - At UHF, the Faraday rotation of the polarization vector can be several revolutions. Thus transmitting and receiving a single polarization can result in large echo signal loss. It can be assumed that linear polarization is transmitted and both vertical and horizontal polarizations are received. Hence two reference channels are processed with all the attendant doppler filtering and integration needed to detect long range targets. After the signal-to-noise ratio is enhanced the signal levels in the two channels are compared and the largest used for detection and range estimation.

3.1.2.7 Clutter Considerations - Earth surface and weather clutter are problems predominately when the range of the target is beyond the unambiguous range as determined by the PRF. For a low angle search beam the significant ground clutter can extend out to 30 NM and for rain, which is normally below 10,000 feet, the return can extend out to 130 NM. Targets beyond the unambiguous range of the radar may fall in the clutter region. A simple two pulse canceller performs an adequate job of eliminating the ground clutter. However, because of the motion of rain clutter a clutter-locked cancellation scheme is required for attenuation of the clutter.

3.2 SIGNAL PROCESSING FUNCTIONS

The signal processing functions in a radar generally refer to those operations required to translate the received wide bandwidth, noisy RF or IF signals from the antenna to detected, measured, labeled target signals of low data rates suitable for handling by the control center. These functions which were historically performed with analog hardware have been increasingly implemented with digital techniques. The advent of CCD's has combined the sampled data nature of digital systems with the continuous amplitude structure of analog hardware. This section summarizes the characteristics of sampled data systems and the manner they are related to key signal processing functions. The important qualitative and quantitative measures of signal processing systems are discussed.

3.2.1 Sampled Data Characteristics

3.2.1.1 Sampling of Real Low Pass Signals - In the implementation of signal processing systems with CCD's the analysis and design must first consider the special requirements of sampled data systems. A brief overview of sampled data systems is presented as background to the development of performance characteristics for various CCD subsystem and systems configurations.

Figure 8 depicts the time waveform and spectrum of a number of sampled data

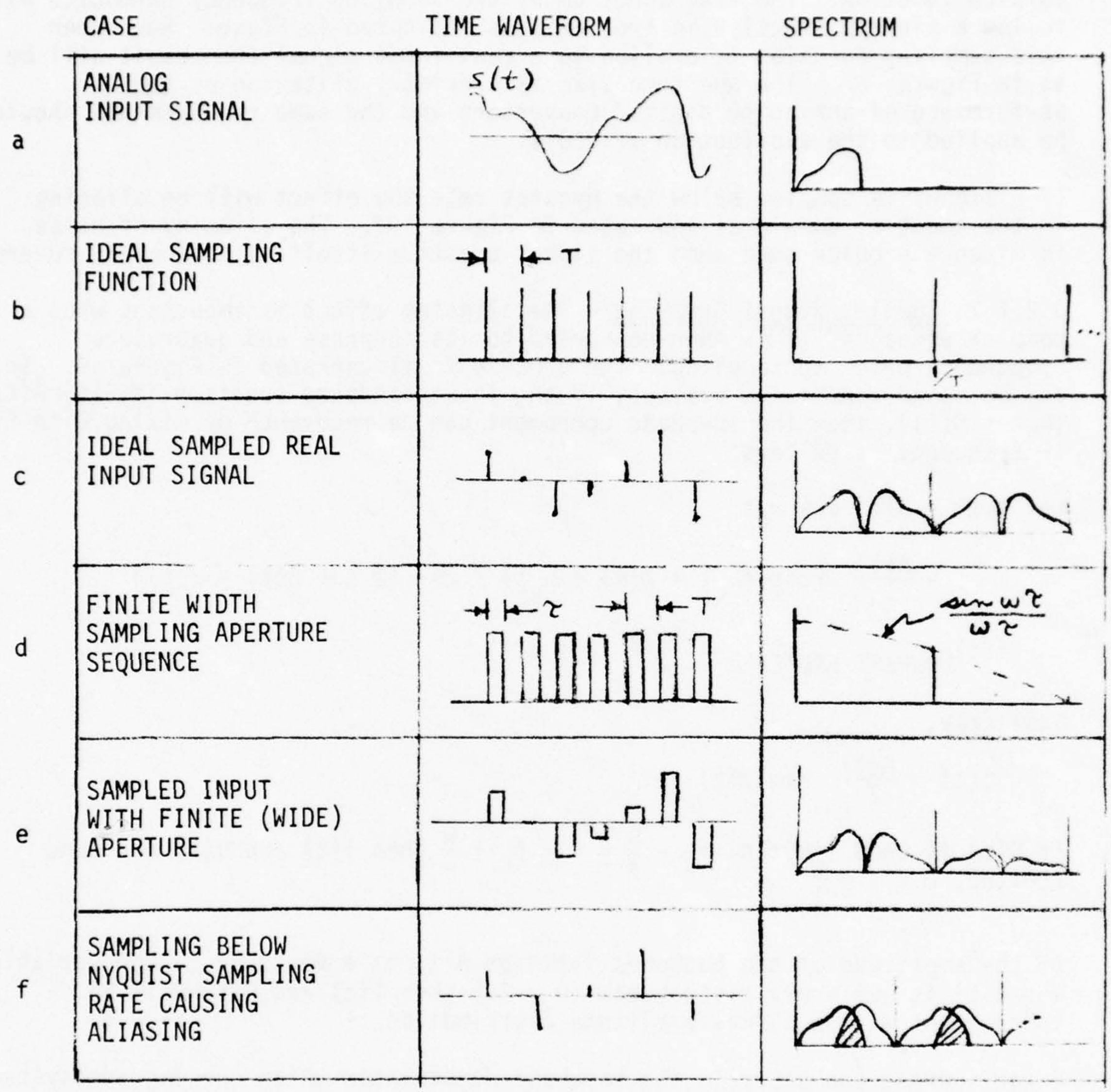


FIGURE 8. BASIC SAMPLED DATA CHARACTERISTICS

situations. In Figure 8a, a simple low frequency video signal with its low frequency signal is shown. A single impulse in the time domain produces a flat frequency spectrum. However, a train of impulse functions representing an idealized sampling function creates a series of line spectra at frequencies which are integral multiples of the sampling frequency. In order to sample a signal of low pass bandwidth B the sampling rate must be greater than or equal to 2B. This is usually referred to as the Nyquist sampling criterion. The spectrum of an ideal sampled real signal is shown in Figure 8c. The sampling process creates sideband replicas of the sampled signal about the harmonics of the sampling frequency.

The sampling function will generally not be ideal but will have a finite

aperture. This finite aperture will limit the frequency content of the sampled function. The line spectrum of the sampling frequency harmonics will follow a sin x/x function in frequency as indicated in Figure 8d. When this sampling function is applied to a real input signal the result will be as in Figure 8e. The aperture size is a primary criterion on the performance of analog to digital converters and the same requirements should be applied in the application of CCD's.

If a signal is sampled below the Nyquist rate the effect will be aliasing in the spectral domain as indicated in Figure 8f. The aliasing of noise is often a problem even when the signal spectrum itself is adequately covered.

3.2.1.2 Complex Signal Sampling - The aliasing effect is important when a complex signal at IF is down-converted to its in-phase and quadrature components prior to sampling. The process is illustrated in Figure 9. In the baseband conversion process, if the input bandpass function is $S(t)=A(t)\cos(\omega_c t + \phi(t))$, then the in-phase component can be recovered by mixing with the IF frequency as follows.

Let $I(t) = S(t) \cos \omega_c t$

$$= \frac{A(t)}{2} \left[\cos(\omega_c t + \phi(t) + \omega_c t) + \cos(\omega_c t + \phi(t) - \omega_c t)\right]$$

$$I(t)_{\text{LOWPASS FILTERED}} = \frac{A(t)}{2} \cos \phi(t)$$

Similarly,

$$Q(t) = \frac{A(t)}{2} \sin \phi(t)$$

If $S(t)$ is band limited, $f_c - \frac{W}{2} \leq f \leq f_c + \frac{W}{2}$ then $I(t)$ and $Q(t)$ are band limited, $0 \leq f \leq \frac{W}{2}$.

If the amplitude of the bandpass function $A(t)$ is a Gaussian random variable and $\theta(t)$ is uniformly distributed $(0 - 2\pi)$ then $I(t)$ and $Q(t)$ will be independent with a normal amplitude distribution.

Error sources can occur in the baseband demodulator which can degrade system performance. Quadrature errors are caused by the two mixing IF signals not being precisely shifted in phase relative to each other by 90 degrees. Amplitude and phase tracking errors and low pass filter distortion can also degrade performance.

One can calculate the noise increase from aliasing due to the low pass filter characteristics. An example is shown in Figure 10 for Butterworth and elliptic filters employed with sampling rates close to Nyquist. The noise increase varied up to 0.4 dB for Nyquist sampling and 0.1 dB for a sampling rate 1.1 times Nyquist. This example also assumed the signal spectrum was Hamming weighted in the signal processor. In this example a limit was placed on the phase distortion so that the higher pole filters which have higher phase distortion are used only at the higher sampling rates. The curve indicates the regions where the filters can be used without compensation while supporting sidelobes greater than 40 dB down. It should be noted that appropriate phase compensation will eliminate this limitation.

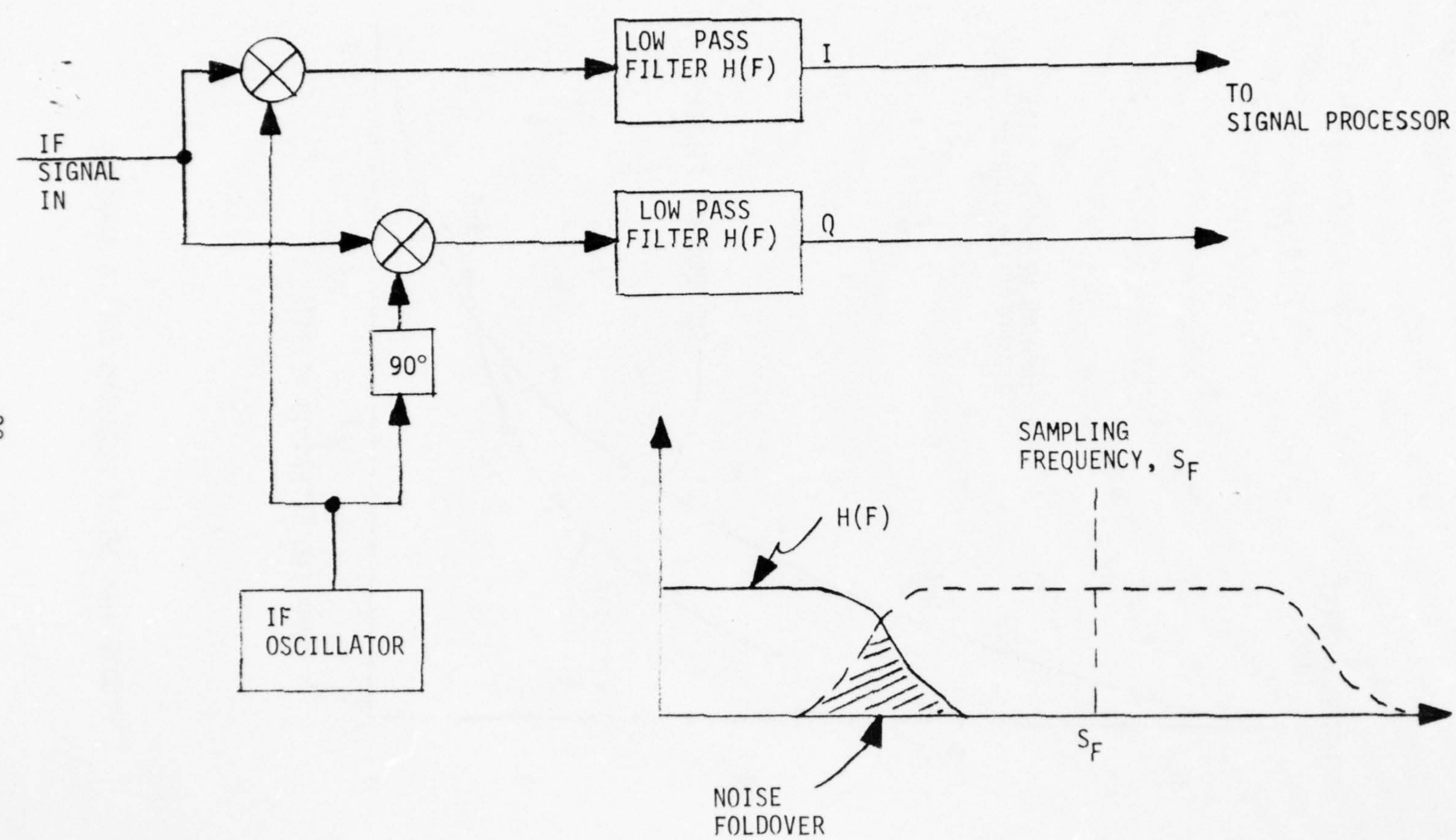


FIGURE 9. BASEBAND CONVERTER

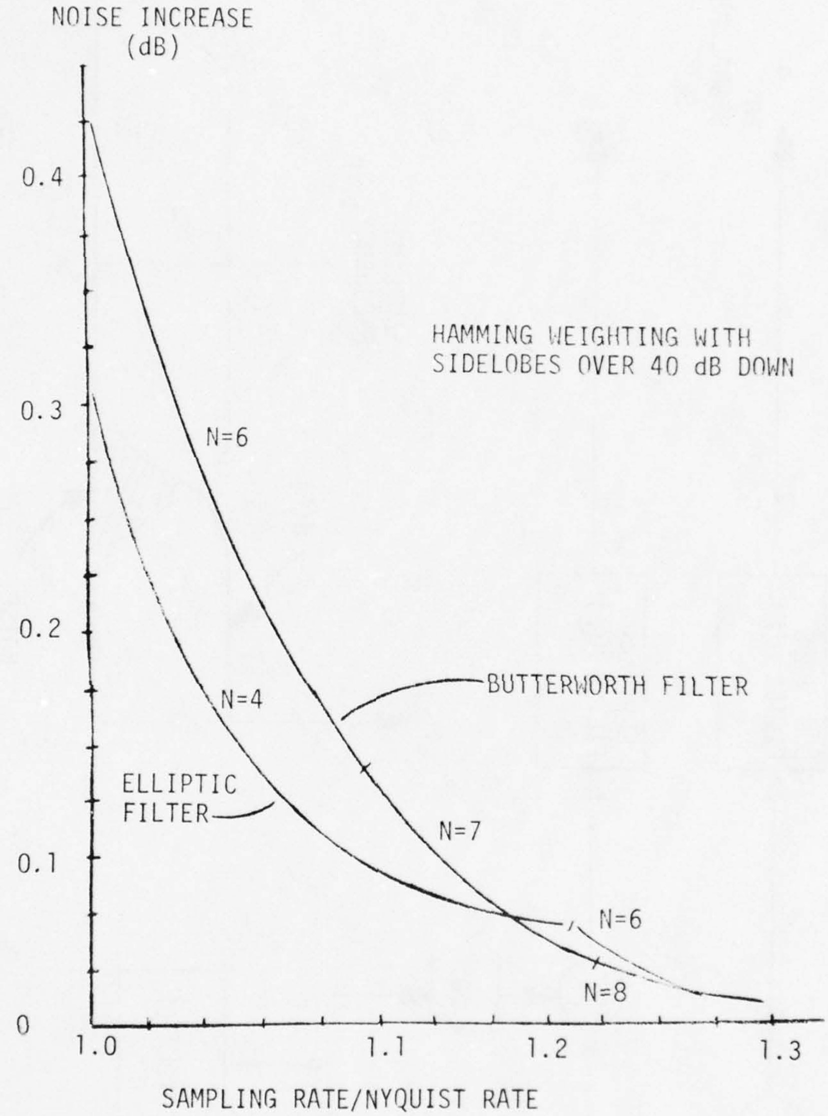


FIGURE 10. NOISE ALIASING DUE TO SAMPLING

3.2.2 Signal Processing Functions

A generalized block diagram of a radar signal processing system is shown in Figure 11. Virtually all of the functions listed can be implemented with CCD's as indicated by the dotted items. If one extends the CCD applications to digital logic implementation, CCD's can be used for all functions. The functions in Figure 11 can be implemented with a basic set of signal processing elements. These are:

- Delay Elements
- Storage Elements
- Integrators
- Arithmetic Functions (Add, Subtract, Multiply, Divide)
- Tapped Delay Lines
- Transversal Filters
- Recursive Filters
- Switches

These elements can either be implemented as part of a CCD or implemented in an analog technique on a CCD integrated circuit. The primary effort relative to CCD performance evaluation for this study has been to identify the key functional elements which are implemented as CCD's and determine their performance as a function of the CCD parameters themselves. The performance level of a full CCD signal processing system can be extrapolated from the constituent elements.

3.2.3 Parameter Ranges of Key Signal Processing Elements

Depending on the radar application, the signal processing functions listed in Figure 11 will have widely varying requirements. The requirements imposed on a signal processor by the long range satellite search radar will not cover the full gamut of potential CCD hardware specifications. Table 21 lists the parameter variations which may be encountered in a large variety of radar systems. Regardless of the level of achievement in a technology toward the implementation of radar signal processing, there will be new applications which cannot be practically met. Thus, the bounds given in Table 21 represent typical requirements rather than extreme. The application of CCD's therefore can best be assessed on an individual case basis. The performance level of CCD's as a function of basic operational parameters as given in Section 6.0 will provide a useful tool in this assessment.

3.3 CCD SIGNAL PROCESSING IMPLEMENTATIONS

Figure 12 shows a typical radar signal processing system with the elements which are candidates for CCD implementation in dark outline. From a hardware viewpoint in typical radar systems, these elements constitute a major part of the signal processor size and cost. This section describes alternative CCD implementation techniques for the principal hardware function of pulse compression, storage and spectral analysis. Details of the CCD structure itself in relation to developing a model for simulation are developed in Section 4.0.

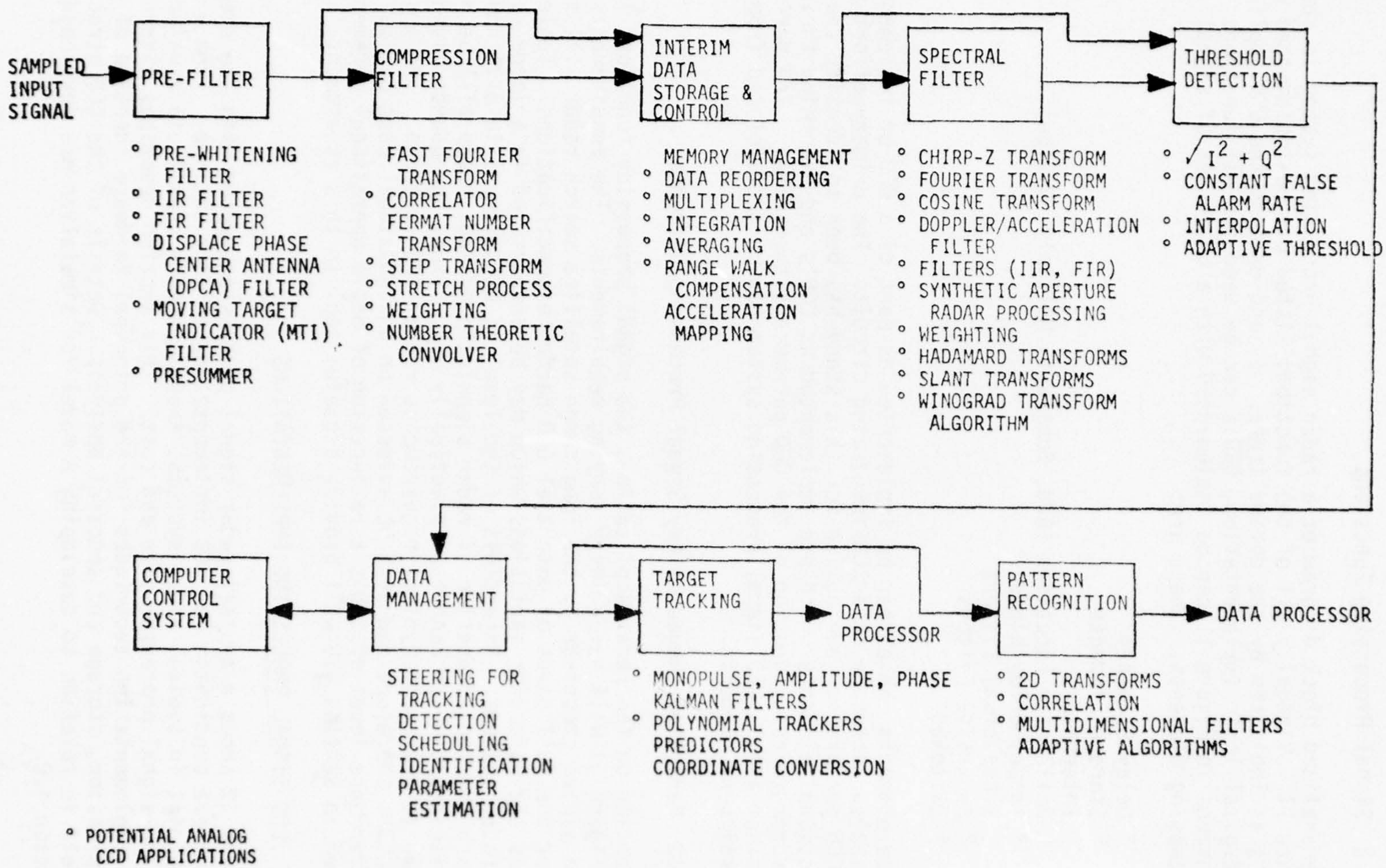


FIGURE 11. GENERALIZED RADAR SIGNAL PROCESSING FUNCTIONS

TABLE 21. PARAMETER RANGES OF SIGNAL PROCESSING FUNCTIONAL ELEMENTS

ELEMENT	SIGNAL PROCESSING FUNCTIONS	CLOCK RATE	NUMBER OF DATA SAMPLES	DYNAMIC RANGE	SPECIAL FEATURES DESIRABLE FOR SOME APPLICATIONS
Delay	Time Alignment and Data Reordering In Most Signal Processing Functions	50 kHz-100 MHz	1-1000	30 - 80 dB	° Programmable Delay ° Data Recirculation
Storage	Data Storage Up To Length of Time Data is in Signal Processor e.g., Target Dwell Time	Load/Unload 50 kHz-100 MHz Store Up to 12 sec.	10-100,000	30 - 80 dB	Random Access
Transversal Filter	FIR Filters, CFAR IIR Filters, Averaging Convolvers, Correlators, Transforms, Interpolation	50 kHz-100 MHz	10-25,000	Input 30 - 60 dB Output 40 - 80 dB	° Programmable Weights ° Internal Reference Store ° Variable Length
Operations	Switching, Arithmetic Functions, Integration	50 kHz-100 MHz	-	30 - 80 dB	

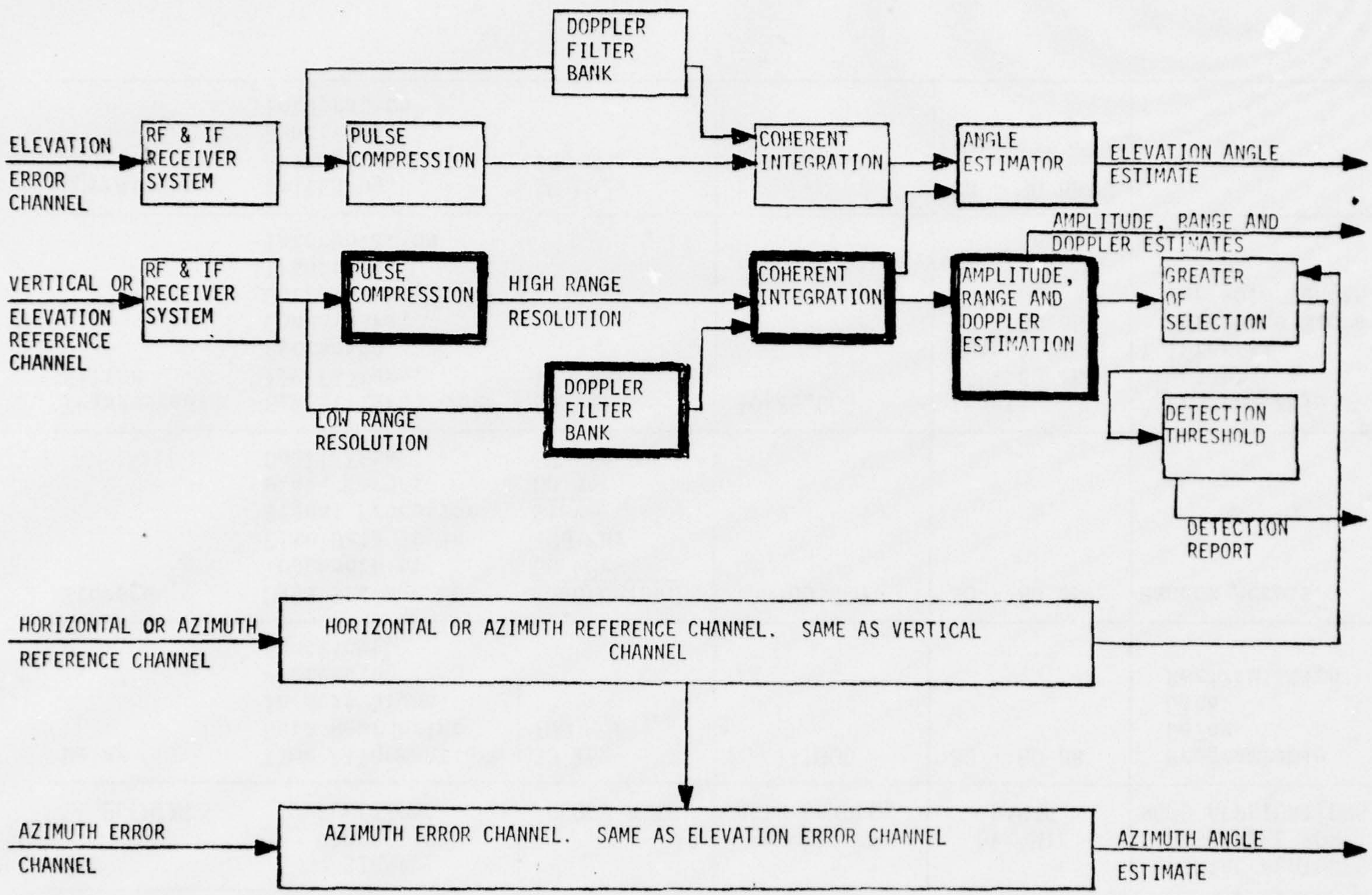


FIGURE 12. RADAR SIGNAL PROCESSING SYSTEM

3.3.1 Pulse Compression

3.3.1.1 Tapped Delay Line Pulse Compression Filters - The output y(t) of a matched filter implemented via convolution of an input signal s(t) with the impulse response of the matched filter h(t) = x(-t) where x(t) is the transmitted waveform;

$$y(t) = \int_{-\infty}^{\infty} s(\tau)\, h^{*}(t-\tau)\, d\tau$$

The signal and filter functions are generally represented as complex in-phase and quadrature samples for sample data operations. Thus a physical realization of the filter function must accommodate the complex multiplication operation, which, for a matched filter is

$$(a + jb)\,(c - jd) = ac + bd + j(bc - ad)$$

A tapped delay line matched filter, therefore, takes the form of Figure 13. CCD's are ideally suited for implementing this function because of their serial structure. The variable weight tapped delay line can be implemented on a CCD using the well known electrode weighting technique [2] shown in Figure 14. In this method, the filter weights are built into the basic physical structure of the CCD gates.

An alternate method for constructing a CCD transversal filter is to place a weight on a CCD floating gate tap output. This latter technique is more amenable to the development of programmable transversal filters. Programmability is a desirable feature in a radar pulse compression system since it permits the tailoring of a transmitted waveform to a specific operational requirement.

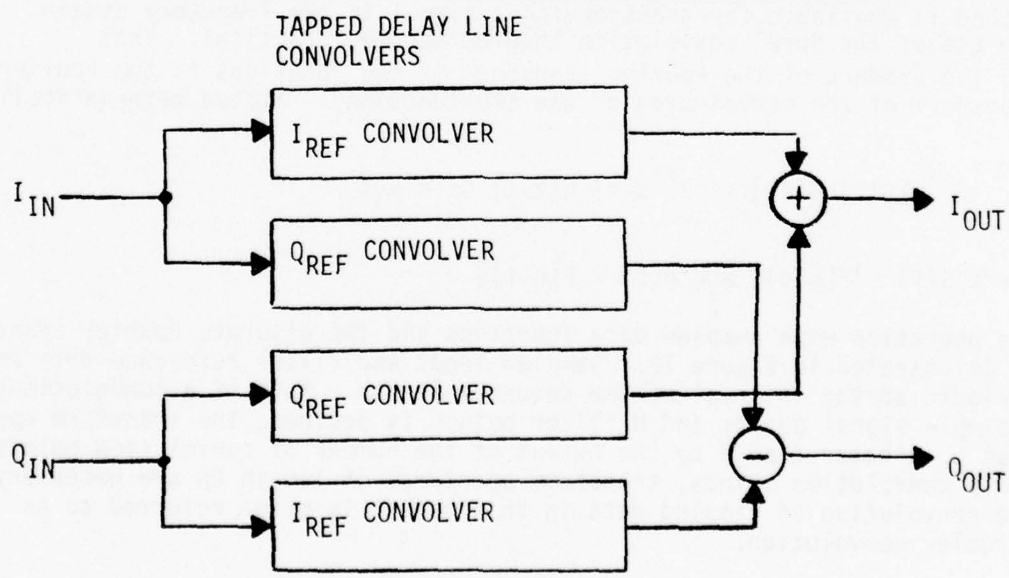


FIGURE 13. TAPPED DELAY LINE MATCHED FILTER

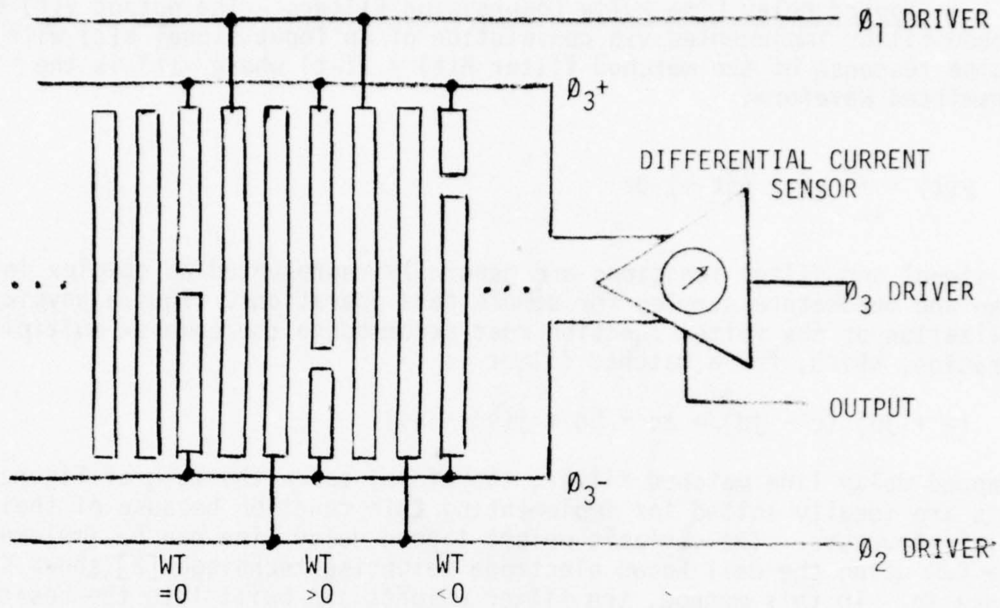


FIGURE 14. SPLIT GATE CCD WEIGHTING TECHNIQUE WITH 3-PHASE CLOCKING

The performance level of CCD transversal filters will depend on the transfer efficiency and noise associated with the charge transfer process and on the realizable tap weight accuracy.

3.3.1.2 Matched Filtering Using Spectral Multiplication - If a convenient method is available for transforming a signal to the frequency domain, the use of the Borel convolution theorem becomes practical. That is, the product of the Fourier transform of two functions is the Fourier transform of the convolution of the two functions. Stated mathematically,

$$F^{-1}\,[S(f)\;H(f)] \equiv \int_{-\infty}^{\infty} x(\tau)\; h(t-\tau)\; d\tau = y(t)$$

where $S(f) = F[s(t)]$ and $H(f) = F[h(t)]$.

The operation with sampled data functions and the discrete Fourier transform is illustrated in Figure 15. Sampled input and filter reference data are periodic at the interval of the sequence length. Thus if a convolution of N sample signal points and N filter points is desired, the transform aperture must be greater than N to the extent of the number of convolution points. For N convolution points, transform apertures of length 2N are necessary. The convolution of sampled data in this manner is often referred to as circular convolution.

The fast Fourier transform (FFT) algorithm has provided an efficient method for calculating the discrete Fourier transform (DFT) of a set of sampled data

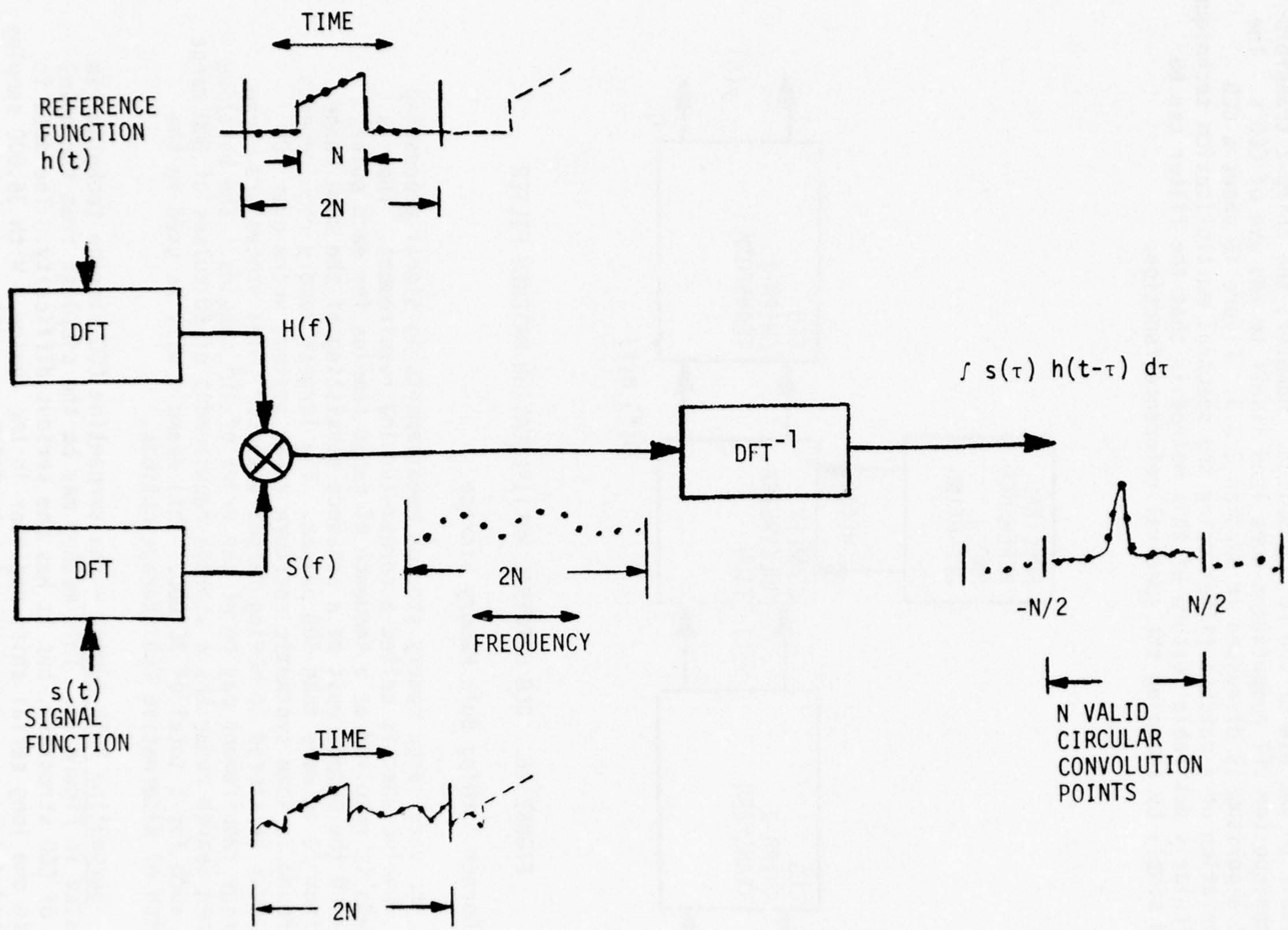


FIGURE 15. ILLUSTRATION OF CONVOLUTION BY SPECTRAL DOMAIN MULTIPLICATION WITH SAMPLED DATA

using digital techniques. The serial structure of CCD's does not lend itself to the use of the FFT algorithm. However, the chirp-Z transform [3] technique for DFT computation does lend itself to the use of CCD's. The chirp-Z algorithm is discussed in Section 3.3.3. Figure 16 shows a CCD implementation of a matched filter using the spectral multiplication technique. A particularly desirable feature of this method is that the filter can be changed simply by changing the spectral reference function.

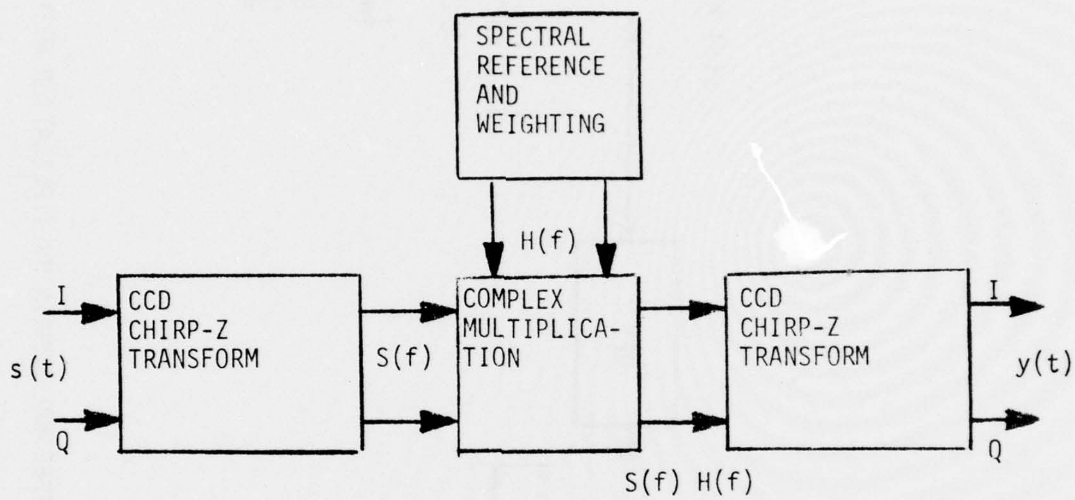


FIGURE 16. CCD SPECTRAL MULTIPLICATION MATCHED FILTER

3.3.2 Corner Turning Bulk Memory Storage

Many of the very large memory storage requirements in signal processing systems involve what is called a corner-turning requirement. That is while data is received as a sequence of range samples for each pulse transmitted the output must be a sequence consisting of the same range sample from 10 to more than 500 pulses. The largest memory requirements can be found in some synthetic aperture radar systems where over 10^6 samples must be stored to moving target detector (MTD) processors where the storage requirement may be of the order of 10^4 samples. The baseline long range search radar has a storage requirement of 60 pulses of 600 range samples each for a total of 36,000. This example will be used in the discussion of alternative CCD storage options.

3.3.2.1 Serpentine Bulk Memory - The serpentine CCD storage technique is illustrated in Figure 17. This method may be the simplest from the point of view of CCD structure, but it has one serious difficulty. The data is loaded in one long serial shift register in the device. With 36,000 samples to be loaded in sequence any transfer inefficiency will seriously degrade the samples passed through the entire device. A 10^{-4} transfer loss which is

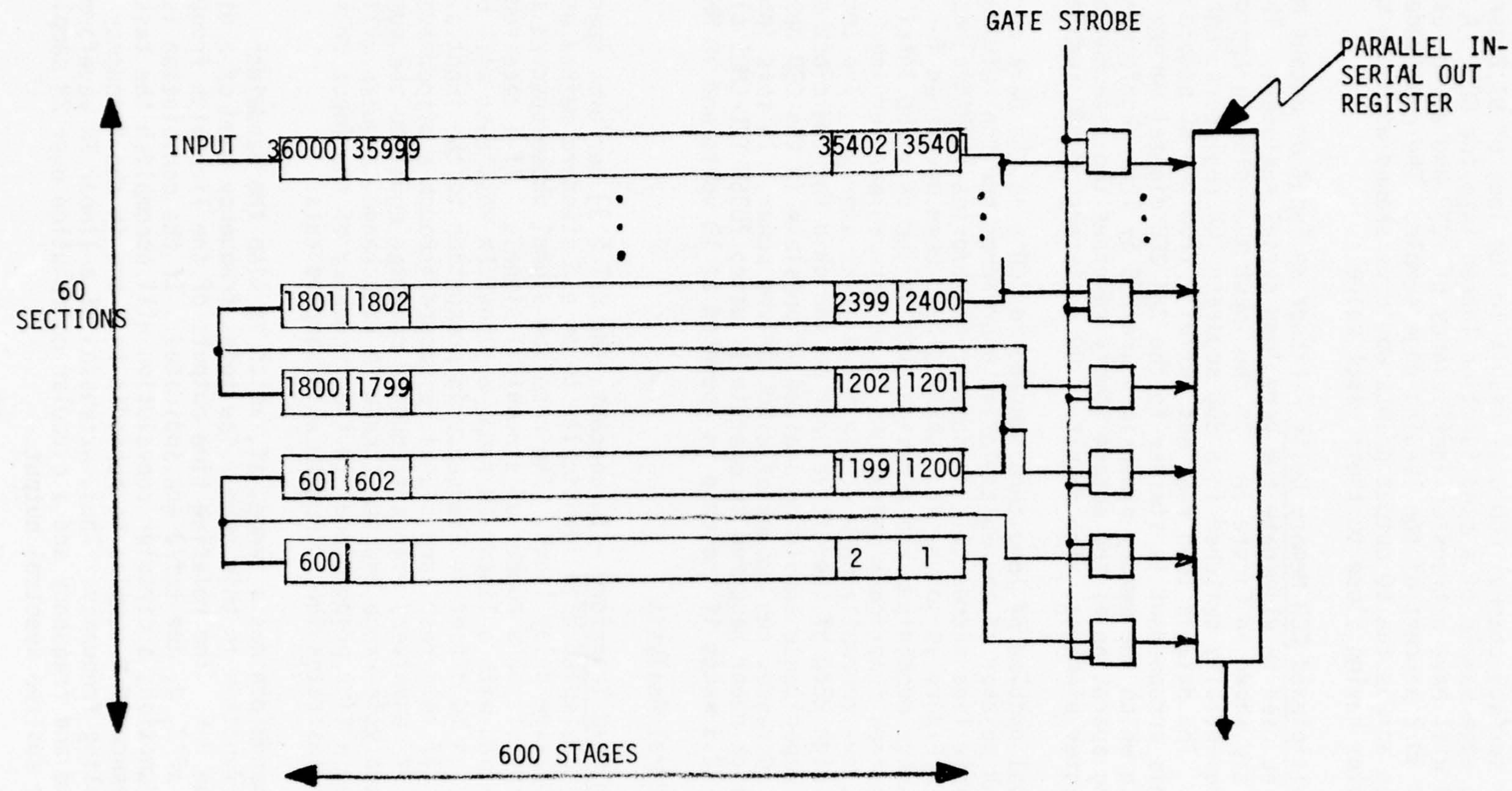


FIGURE 17. SERPENTINE BULK MEMORY

typical for surface channel CCD will result in the loss of 97.2 percent of the leading edge sample of a step function loaded into the CCD. A buried channel CCD will have a transfer inefficiency of 10^{-5} and would result in the loss of 30.2 percent of the leading edge sample. The amplitude distribution across the 60 output points would be skewed with the most recent samples having close to their exact value.

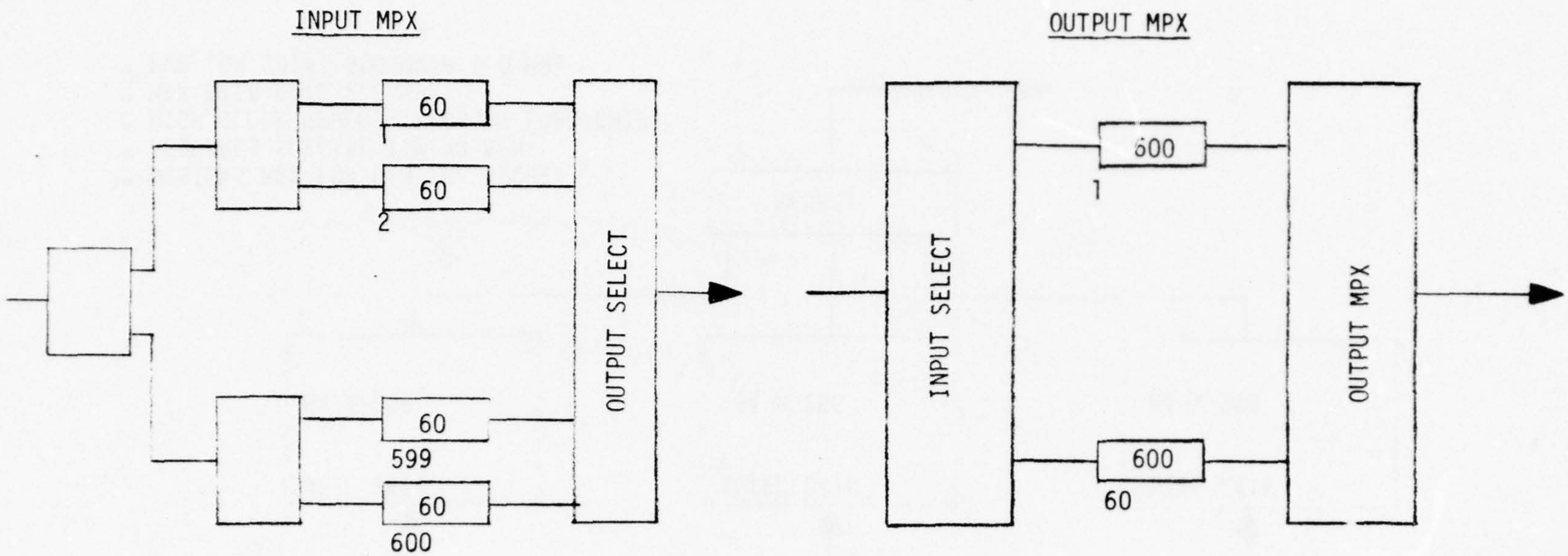
3.3.2.2 Multiplexed CCD Memory Cells - Either an input or output multiplexing method can be used to eliminate the very long serial registers. The two approaches are shown in Figure 18. In the input multiplexing approach, the input is sequentially switched into 600 separate CCD registers, one for each range cell. The data is then read out serially from one 60 sample register at a time. This arrangement is similar to the 32K CCD digital memory design of Fairchild in which the memory dimensions are 256 by 128. Performing a multiplexing operation at the output simply reverses the size and number of CCD register elements. The result is 60 registers of 600 samples each.

The principal problem of long term storage in CCD's is the dark current build up and neither of the multiplexing approaches nor the bulk memory using multiple line addressable random access memories (LARAM's) as indicated in Figure 19 solves it. LARAM's have been developed for use as digital storage mechanisms and a design such as the 64 x 256 Intel 2416 has the required functional operations to perform corner turning. However, these units are currently only viable for digital storage. The Intel design has a very high 2800 pf capacitive load on the chip for the clock input. This high clock capacitance should be avoided if possible in the CCD design as it greatly increases the amount of clock driver power. In this instance, the peak clock power required to operate it using 75365 TTL-CMOS clock drivers is 12.5 watts if the chip is operated at 10 volts and 10 MHz.

3.3.3 Spectral Analysis

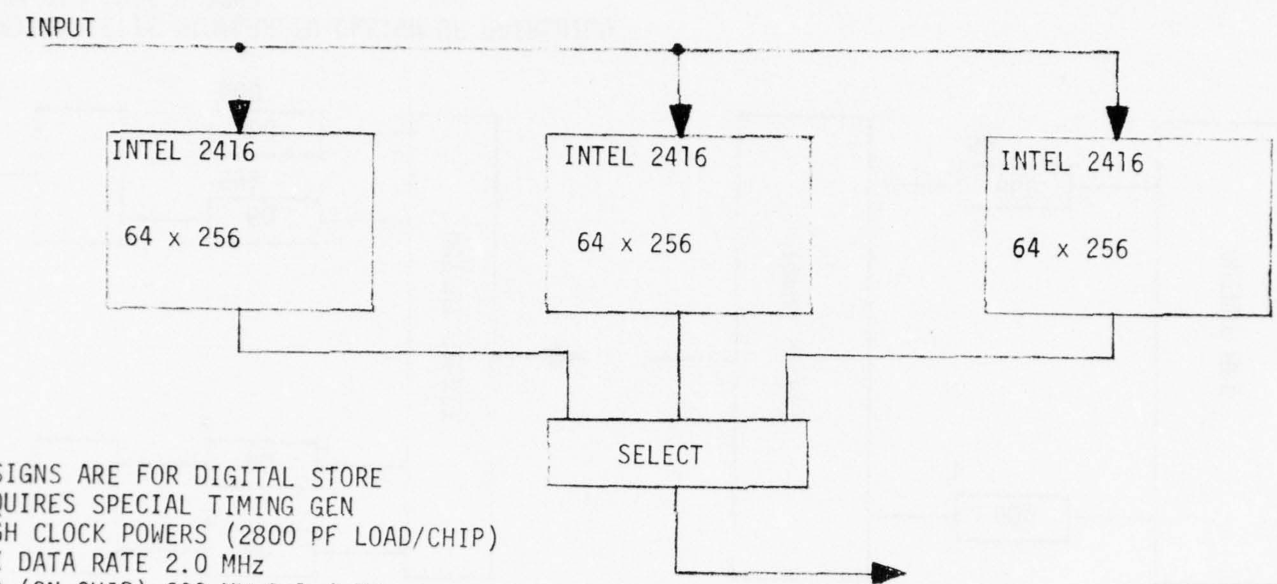
3.3.3.1 Chirp-Z Transform - In concept, the CZT [3] performs spectral analysis with sampled data identically to an old standard method used with analog dispersive delay lines. The received signal whose spectra is to be analyzed consists of a number of sinusoidal signals. If a received CW signal is mixed with a linear FM ramp, a linear FM resultant will be produced which is offset in frequency in proportion to the input signal frequency. If this resultant signal is passed through a dispersive line (or linear FM convolver) with a frequency coverage equal to the sum of the frequency analysis range and the linear FM ramp range, a pulse will be outputted at a time proportional to the frequency of the input CW signal. Figure 20 illustrates the principle with sampled data.

The input bandwidth has a range, Δf, which is also the bandwidth of the LFM function in this case. The total frequency band of a dispersive line must be $2\Delta f$. The relative time outputs of the line with frequency inputs of $-\Delta f/2$, 0, and $+\Delta f/2$ are indicated. If the convolution is done via a sampled function, a circular convolution will accomplish the task. Recall that a sequence of N samples is periodic in N and in the frequency domain at the sampling frequency. Thus, extension of a linear FM waveform occurs in both time and frequency and a circular convolution over 2N samples will provide the desired spectral output.



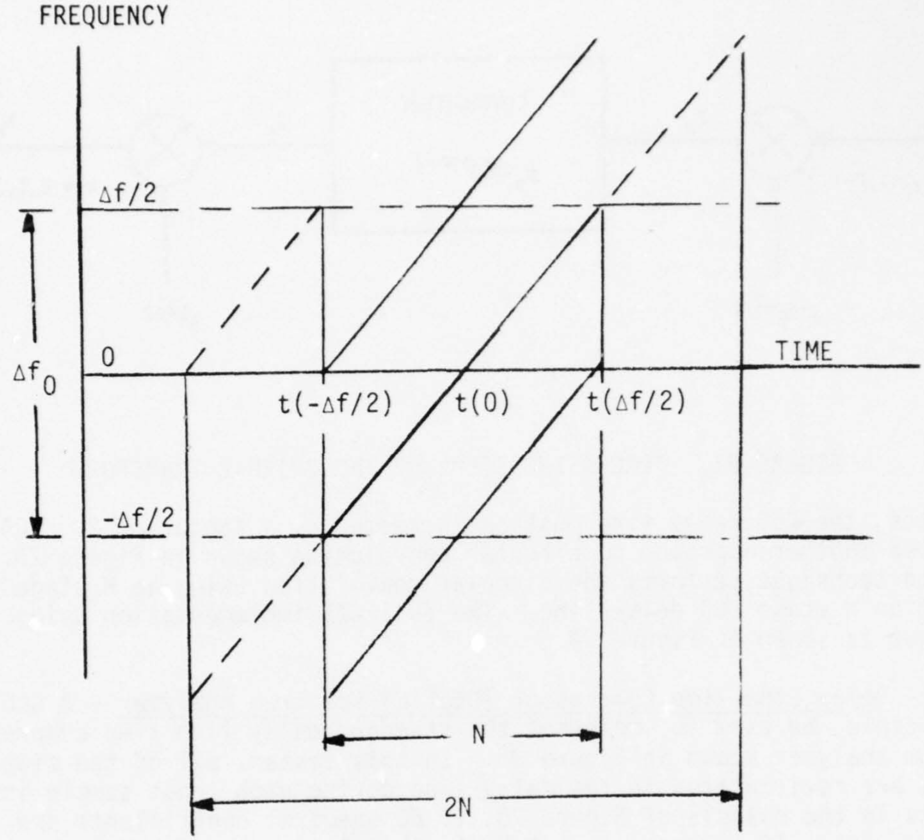
PRINCIPLE IS SIMILAR TO DESIGN OF FAIRCHILD
32K CCD (256 x 128)

FIGURE 18. SIMPLE MULTIPLEXING BULK STORE



- DESIGNS ARE FOR DIGITAL STORE
- REQUIRES SPECIAL TIMING GEN
- HIGH CLOCK POWERS (2800 PF LOAD/CHIP)
- MAX DATA RATE 2.0 MHz
- PWR (ON CHIP) 600 MW @ 1.0 MHz

FIGURE 19. BULK MEMORY USING MULTIPLE LARAM



N = TIME SPAN OF LFM FUNCTION
2N = SUM OF N PLUS RELATED TIME SPAN OF FREQUENCY BAND, Δf

FIGURE 20. CHIRP-Z DFT CONCEPT

The CCD is ideally suited for the computation of the discrete Fourier transform (DFT) via the chirp-Z transform (CZT) because the implementation of the CZT makes use of linear FM convolvers. The basic processing steps of the CZT are shown in Figure 21. The complex input signal (X_p) is mixed with the chirp signal $A^{-p} \cdot B^{p^2/2}$ which produces an offset chirp signal output. This signal (Y_p) is convolved with $B^{-p^2/2}$ in the convolution filter. The convolution peak at the output of the filter occurs at a time corresponding to the frequency of the input signal. The complex multiplication after convolution corrects the phase bias by multiplication with the reference chirp signal ($B^{k^2/2}$). If the phase information is not required, then the output of the convolution can give the power spectrum. Figure 22 shows the CZT process in more detail. The complex CZT requires real and imaginary baseband processing (I and Q).

The circular convolution can be performed in the CZT using a tapped CCD delay line of 2N stages, where N is the number of samples for which the z-transform is evaluated. Therefore, to increase the number of points that the CZT

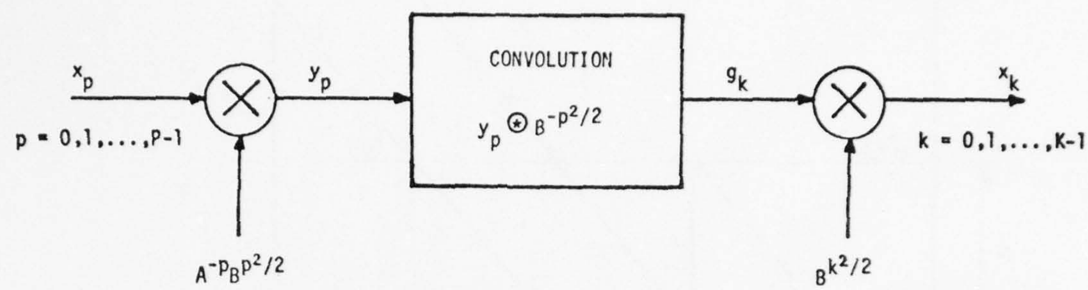


FIGURE 21. PROCESSING STEPS OF THE CHIRP Z-TRANSFORM

evaluates, the CCD delay line must be increased by a factor of 2. RCA has developed another approach to circular convolution shown in Figure 23. This patented technique performs the circular convolution using an N stage tapped CCD and an N stage CCD delay line. The full CZT implementation using the technique is shown in Figure 24.

3.3.3.2 Delay Line Time Compressor (DELTIC) Spectrum Analyzer - A CCD can, in principle, be used to implement the standard delay line time compressor spectrum analyzer shown in Figure 25. In this system, all of the signal samples are recirculated in the delay line during each input sample interval. Thus, as in the example of Figure 25, if 60 spectral coefficients are analyzed with a 60 time sample interval, the clock rate of the system is 60 times the input sample rate. This technique will be limited with CCD's to small numbers of samples (N) because the number of CCD transfers is N^2. For wide bandwidth applications, the clock rate becomes prohibitively high.

3.3.3.3 Stored Coefficient CCD Spectrum Analyzer - Another approach to spectrum analysis with CCD's which avoids the high clock rates of the DELTIC is given in Figure 26. In this case, the samples to be analyzed are loaded into the tapped delay line and held. All of the spectral reference coefficients can be stored on the CCD in a manner similar to a split gate correlator and the coefficients can be read out by impulsing the line. This general method has the advantages of providing any arbitrary transform of the input and operation at clock speeds equal to the sample rate. However, the storage requirement is proportional to N^2 thus limiting the size of the transform.

3.3.4 *Extended Time Bandwidth Applications*

It was indicated in Section 3.2 that time bandwidths at least as high as 25,000 might be encountered for some radar requirements. In fact, the long range search radar application could include a pulse length of up to 2 msec with a 5.0 MHz bandwidth. With a sample rate of 6.0 MHz, the resulting samples required to define the waveform is 12,000. If the spectral multiplication technique were used for matched filtering, DFT's as large as 24,000

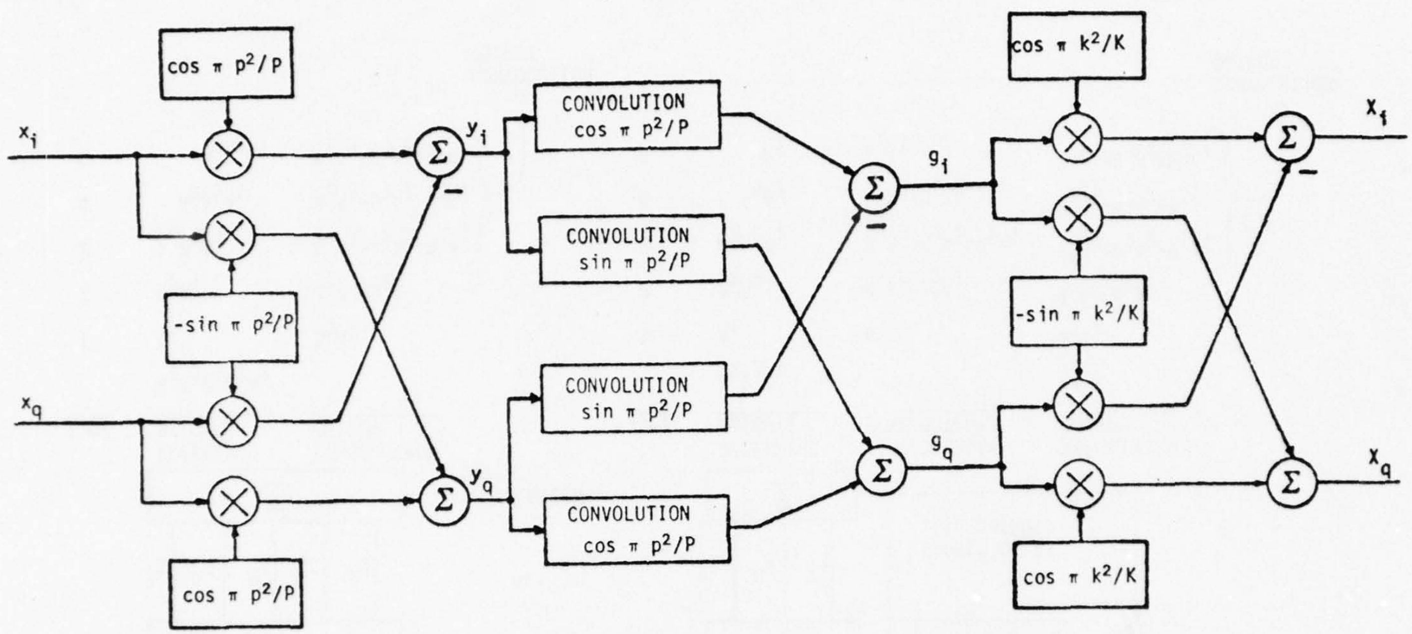
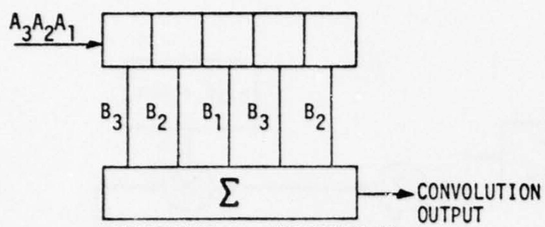
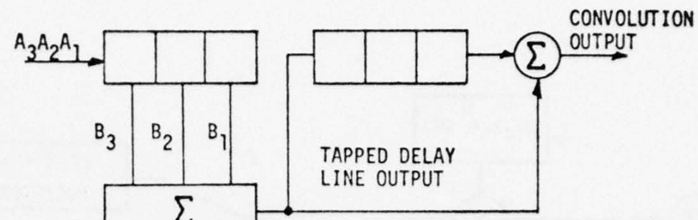


FIGURE 22. FUNCTIONAL DIAGRAM OF THE CHIRP Z-TRANSFORM



TIME	REFERENCE WEIGHTS	CONVOLUTION OUTPUT
	$B_3B_2B_1B_3B_2$	
1	A_1	B_3A_1
2	A_2A_1	$B_3A_2+B_2A_1$
3	$A_3A_2A_1$	$B_3A_3+B_2A_2+B_1A_1$
4	$A_3A_2A_1$	$B_2A_3+B_1A_2+B_3A_1$
5	$A_3A_2A_1$	$B_1A_3+B_3A_2+B_2A_1$

CONVOLUTION OUTPUT

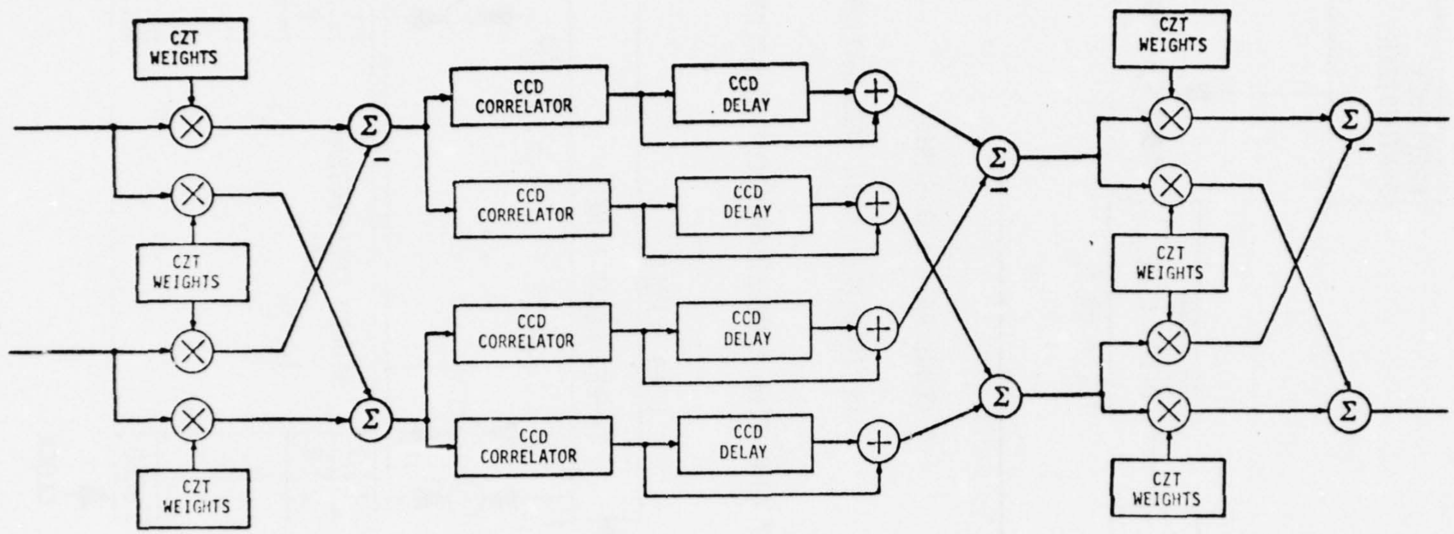


TIME	REFERENCE WEIGHTS	TAPPED DELAY LINE OUTPUT	CONVOLUTION OUTPUT
	$B_3B_2B_1$		
1	A_1	B_3A_1	B_3A_1
2	A_2A_1	$B_3A_2+B_2A_1$	$B_3A_2+B_2A_1$
3	$A_3A_2A_1$	$B_3A_3+B_2A_2+B_1A_1$	$B_3A_3+B_2A_2+B_1A_1$
4	A_3A_2	$B_2A_3+B_1A_2$	$B_2A_3+B_1A_2+B_3A_1$
5	A_3	B_1A_3	$B_1A_3+B_3A_2+B_2A_1$

CONVOLUTION OUTPUT

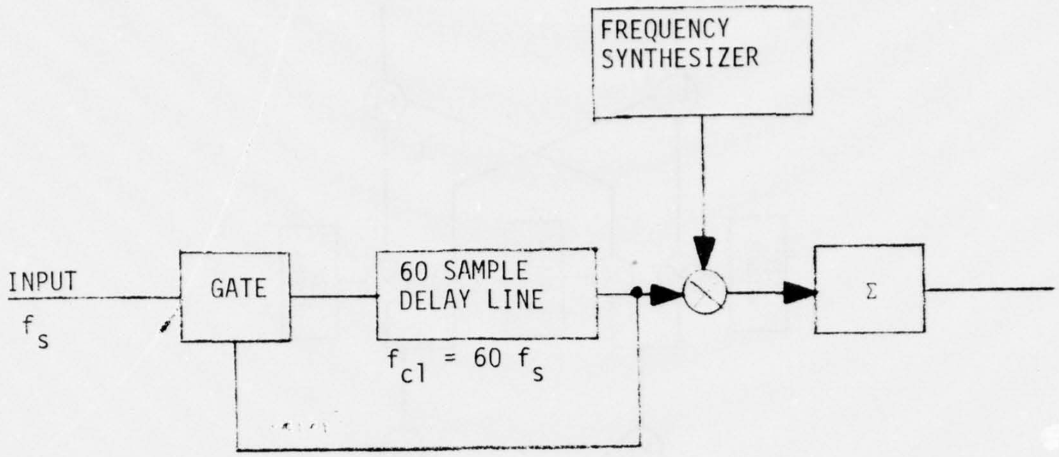
RCA PATENTED PROCESS

FIGURE 23. CIRCULAR CONVOLUTION TECHNIQUE



RCA PATENT PENDING

FIGURE 24. CCD CHIRP Z-TRANSFORM (CZT)



$f_s \geq 60$ KHz

° CLOCK RATE $\geq$ 3.6 MHz

° RECIRCULATED DATA DEGRADATION

FIGURE 25. DELAY LINE TIME COMPRESSOR (DELTIC) SPECTRUM ANALYZER

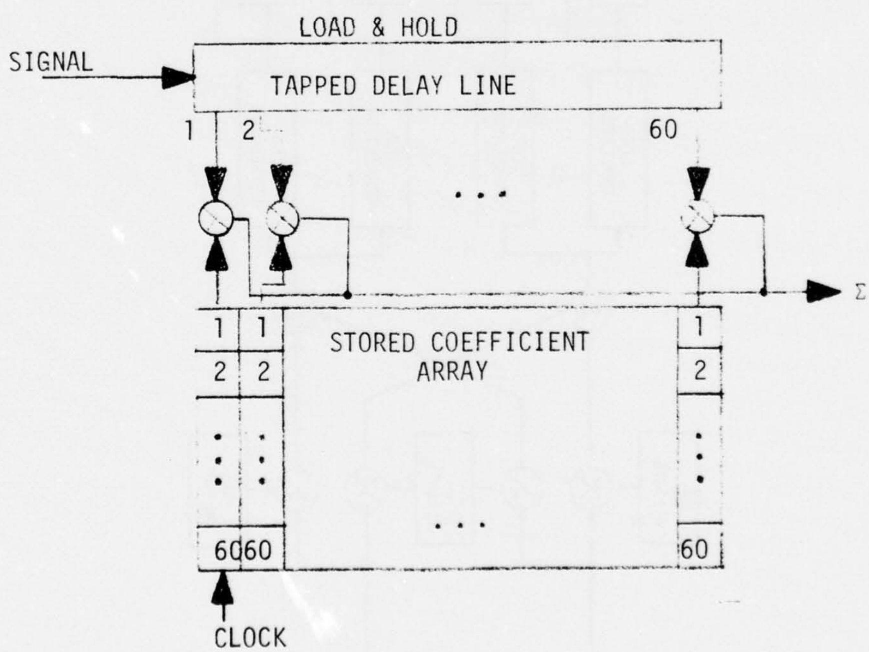


FIGURE 26. STORED COEFFICIENT CCD SPECTRUM ANALYZER

could be required. This section discussed some alternative techniques for processing these large TW products with shorter CCD filters.

3.3.4.1 Step Transform (Sub-Aperture) Technique - The step transform algorithm [4] effectively breaks up a linear FM waveform into sub-apertures which can be more adequately processed with CCD's.

A conceptual diagram of the step transform process is given in Figure 27. The upper portion of the figure indicates the principal functional elements in the processor while a representation of the function itself is given below. The received signal is a linear FM waveform of length T and bandwidth W. This is sampled, A/D converted and multiplied by a linear FM sawtooth whose time bandwidth product of a single "tooth" is approximately equal to $\sqrt{TW}$. The resultant from this operation is a segmented CW waveform of $\sqrt{TW}$ segments whose overall slope is equal to the slope of the original waveform. Each individual segment is then passed into a DFT spectrum analyzer to obtain its exact spectral characteristics. The number of sample points in the deramping sawtooth is equal to the number of sample points in the input DFT aperture.

Successive DFT analysis windows are stored in the data reordering memory forming a time-frequency matrix. Spectral data from a single received linear FM pulse will have amplitude peaks across the matrix beginning at a point corresponding to the range of the target. Fine range resolution is obtained by processing successive diagonals of the data in the time frequency matrix through the second DFT. The output of the second DFT gives the compressed pulse output with a resolution determined by the bandwidth of the waveform. Weighting is applied prior to entering the second DFT to reduce range sidelobes.

The implementation of the DFT in the step transform process can be done with a CCD-CZT. Many of the CZT and step transform functions can be combined so that a functional diagram will be similar to that shown in Figure 28.

The reorder memory function in the step transform algorithm requires that data received on a column by column basis be read out along a diagonal through successive columns. This process is normally accomplished using random access memories in a digital system. However, a technique for accomplishing the diagonalization using serial shift registers has been developed, and its implementation with CCD's is shown in Figure 29. The total register length is approximately equal to the number of samples in the waveform.

3.3.4.2 Extended TW-CZT - A method can be used as indicated in Figure 30 to synthesize a large CZT with smaller CZT segments. In this case, the objective was to synthesize a 24,000 point transform. It is done by combining 24-1000 point CZT's in a sub-aperture approach somewhat akin to the step transform. An inherent problem with any large TW product signal processor is the requirement for storage of the full TW samples. This is exemplified in the sub-aperture CZT by the size of the delay lines. The maximum length in the example is 23,000 stages.

3.3.4.3 Sub-Aperture Convolution - A sub-aperture convolver can be used to reduce the size of the CCD memories in extended time-bandwidth convolvers if not the number of transfers. The concept is shown in Figure 31 where 12,000

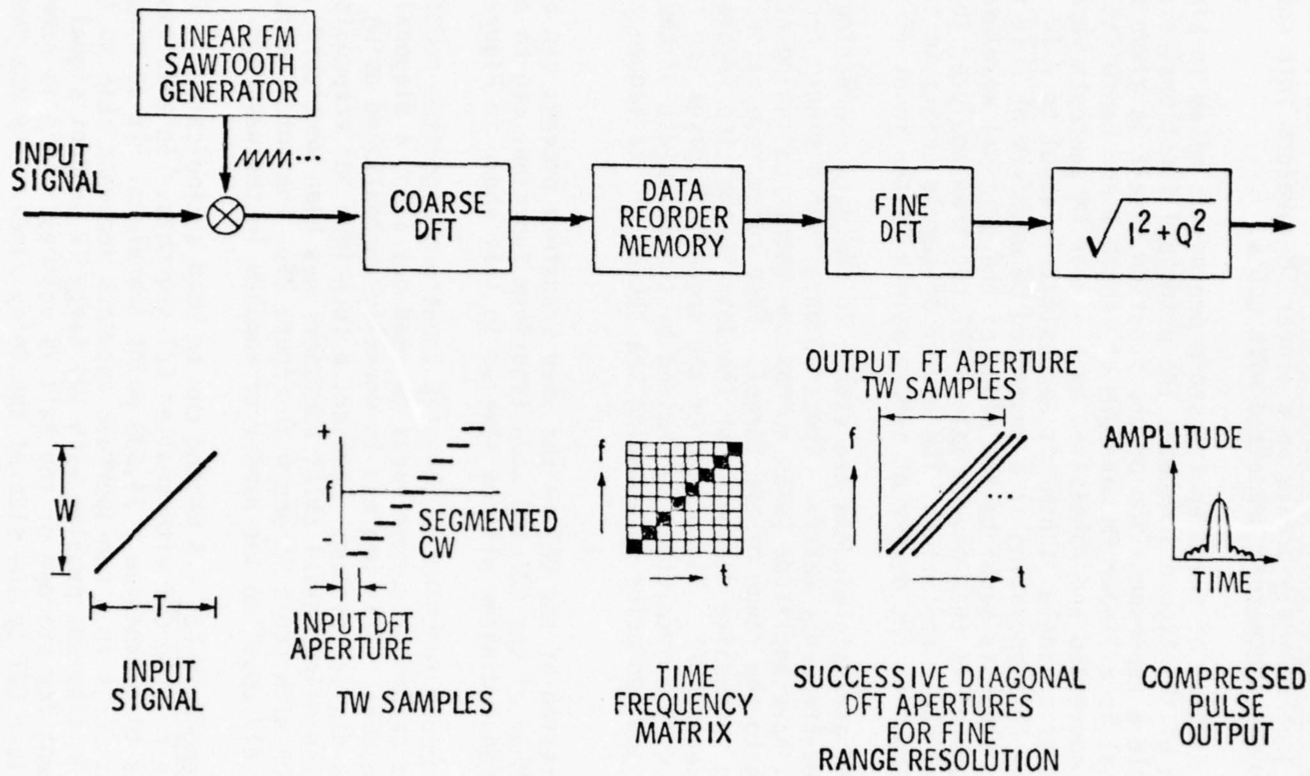


FIGURE 27. STEP TRANSFORM LFM PULSE COMPRESSION PROCESSING

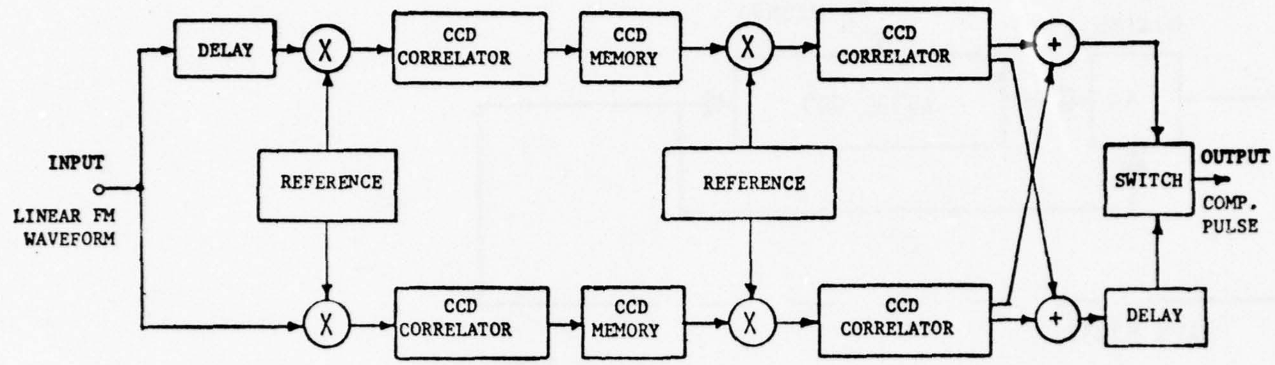
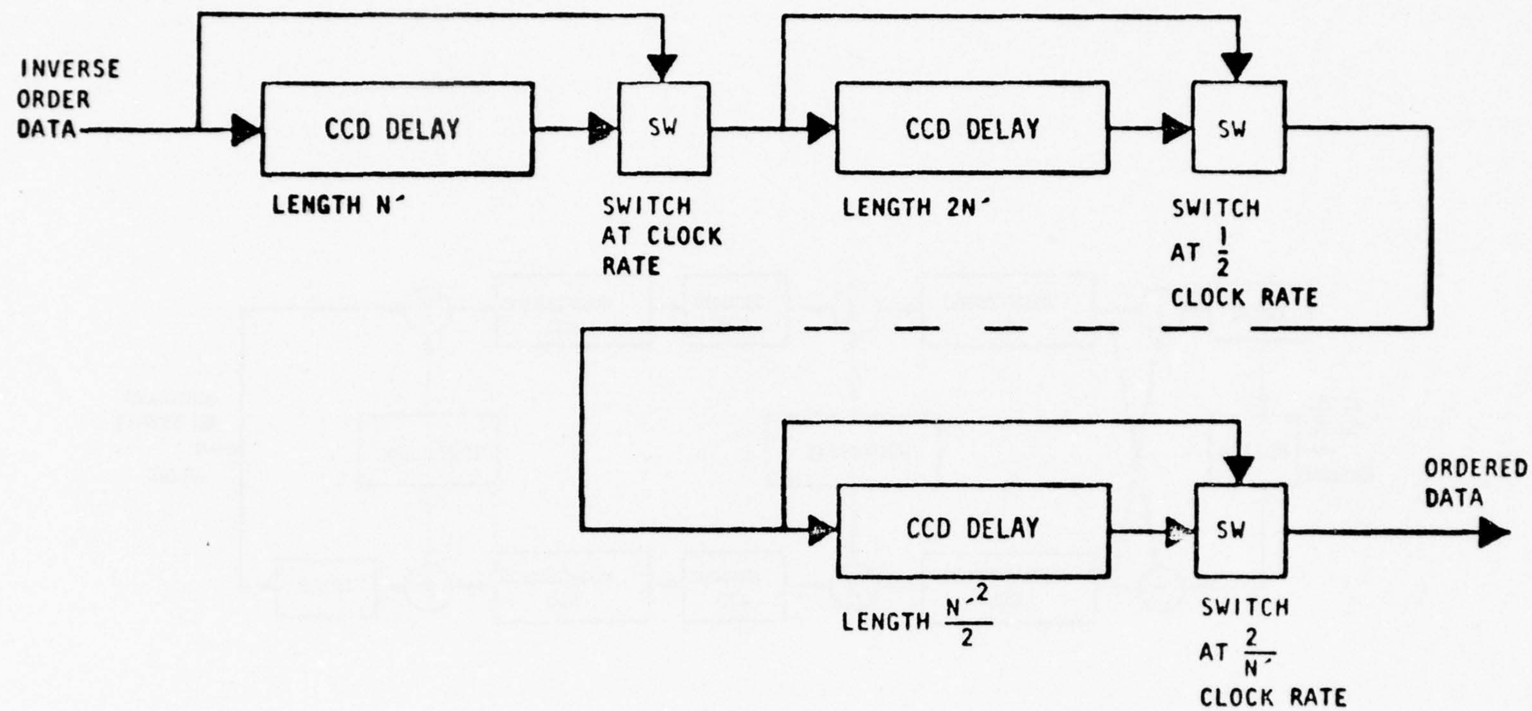


FIGURE 28. FUNCTIONAL BLOCK DIAGRAM OF CCD STEP TRANSFORM PROCESSOR



N´ IS APPROXIMATELY EQUAL TO THE SQUARE-ROOT OF THE TIME-BANDWIDTH PRODUCT

FIGURE 29. CCD REORDER MEMORY

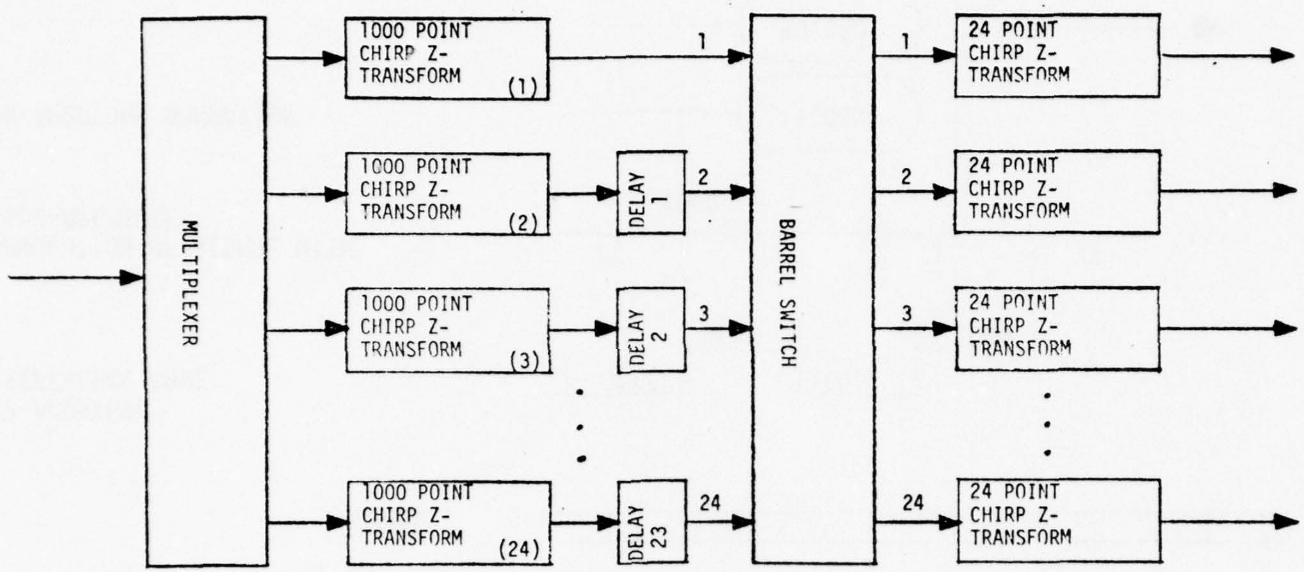


FIGURE 30. 24,000 POINT CHIRP Z-TRANSFORM

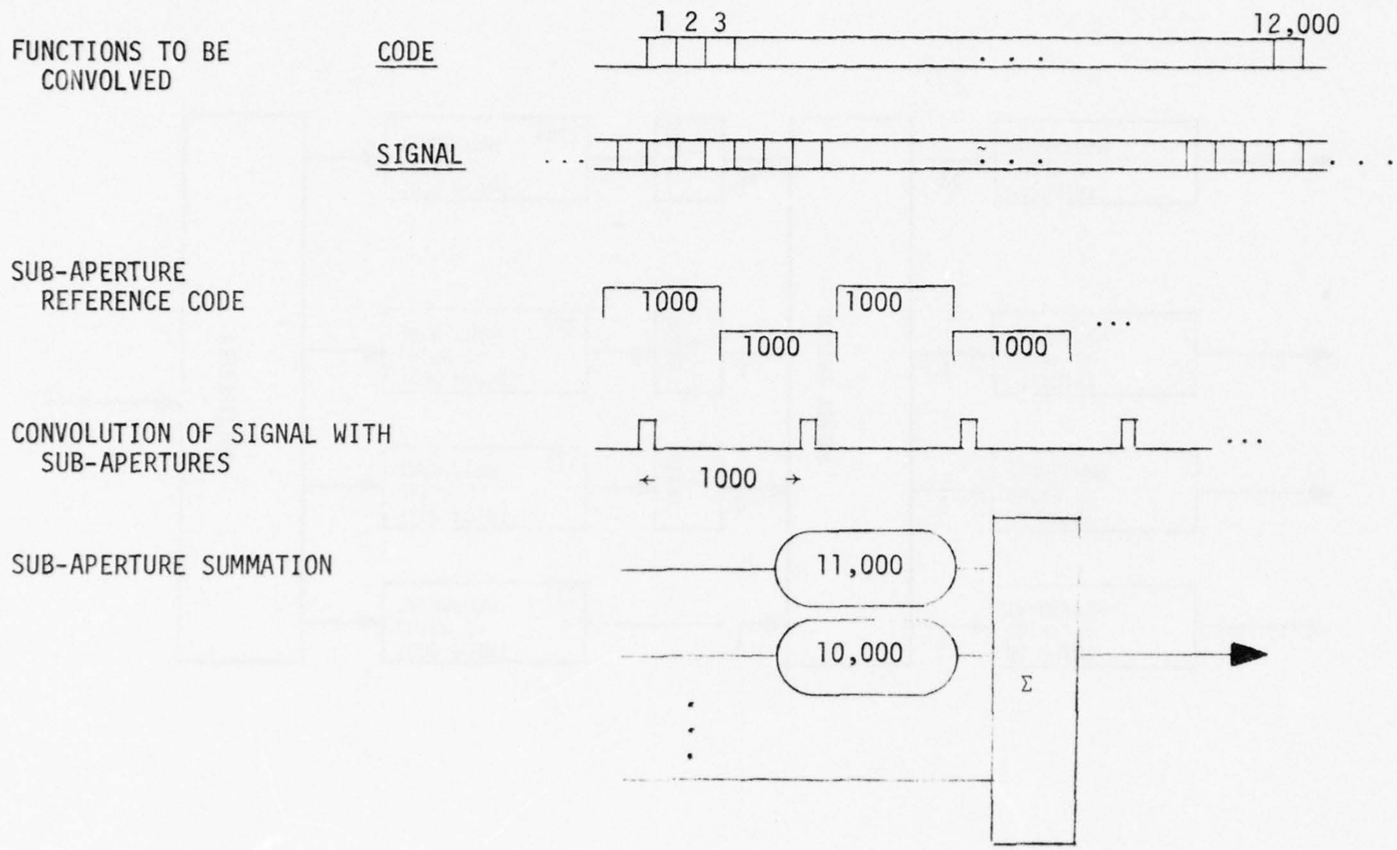


FIGURE 31. SUB-APERTURE CONVOLUTION

sample code and signal samples are to be convolved. If the number of convolution samples desired is limited to 1000 points, the reference code can be broken up into 1000 point samples each of which can be correlated with the appropriate segment of the signal. The resultant is a set of impulses separated by 1000 points which can be summed by the delay line network of Figure 31. An alternative implementation might take the form of Figure 32. In this approach, the input is alternately steered to two programmable CCD convolvers and each 1000 point output is integrated in the recirculating integrator. Here again, the performance limitation due to a large number of transfers in the CCD delay line in the integrator will be a factor.

3.4 BASELINE CCD SIGNAL PROCESSOR

A baseline radar signal processing system was developed from the requirements outlined in Section 3.1. The baseline system features a two step detection process to achieve long coherent integration times for high radial velocity targets. A low range resolution waveform is used on the first step to obtain coarse range and doppler, followed by a high range resolution waveform on the second step with programmed velocity gates for coherent integration with high range resolution.

3.4.1 Baseline System Approach

To achieve coherent integration the target must remain within the range cell during the integration time. For a radial target velocity of 10,000 ft/sec, and a range resolution of greater than 6,070 ft (1NM) the target will pass through the range cell in less than 1 second. In this situation, coherent integration of more than 1 second is not effective. A two step detection process will overcome this range walk problem.

On the first step a low range resolution waveform is transmitted such that the target will not walk through the range cell during the integration interval. A coarse range resolution ($\leq$ 40 NM) and radial velocity resolution (250 ft/sec) will be obtained. In the event of a detection on the first step the second step process is initiated in which a high range resolution waveform ($\leq$ 1 NM) is transmitted.

By using the coarse velocity estimate from the first step, a large part of the target radial velocity can be removed to permit the full coherent integration with the high range resolution. In essence the position of the range cells can be programmed versus time to approximately match the target radial motion and thus reduce the range walk to an acceptable value. The second step provides the desired range and doppler resolution as well as the angle estimates.

The attractiveness of the two step detection approach is that it is not wasteful of radar resources since the second step is not used until a detection is obtained on the first step. Furthermore, since the number of targets beyond 2000 NM is small and normally closely spaced, the second step process is not often repeated as would be the case of widely separated multiple targets.

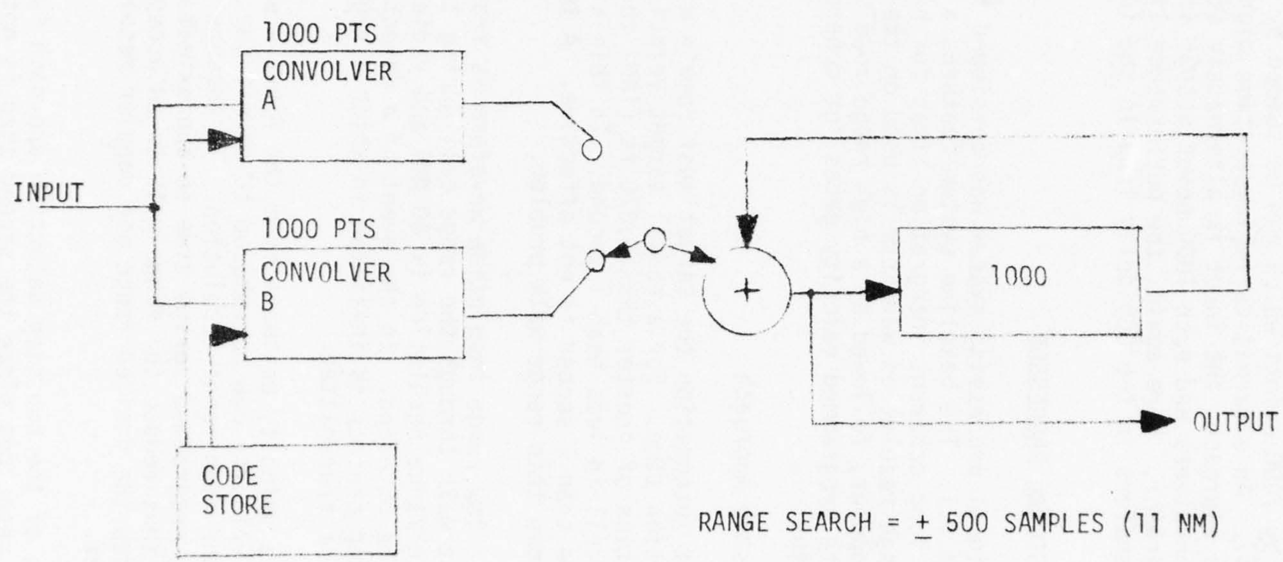


FIGURE 32. IMPLEMENTATION OF SUB-APERTURE CONVOLUTION

3.4.2 Waveforms for the Baseline System

Figure 33 provides a summary of the waveforms proposed in the two step approach. The range resolution of the first step waveform, Figure 33a, is low enough so that the target remains substantially in the range cell for the entire integration interval. In addition the waveform provides a coarse doppler estimation which is used on the second step process to program the range cell such that the target remains in the high range resolution cell over the integration interval.

The higher range resolution on the second step is achieved with a linear FM waveform, Figure 33b, having a bandwidth of 200 KHz. This bandwidth provides a resolution of 1 NM between two targets with an amplitude differential of 10 dB. Resolution in doppler is a function of the coherent integration interval which for a 6 second integration interval is 1/6 Hz. This doppler resolution permits separation of targets within the same range cell but with different velocities.

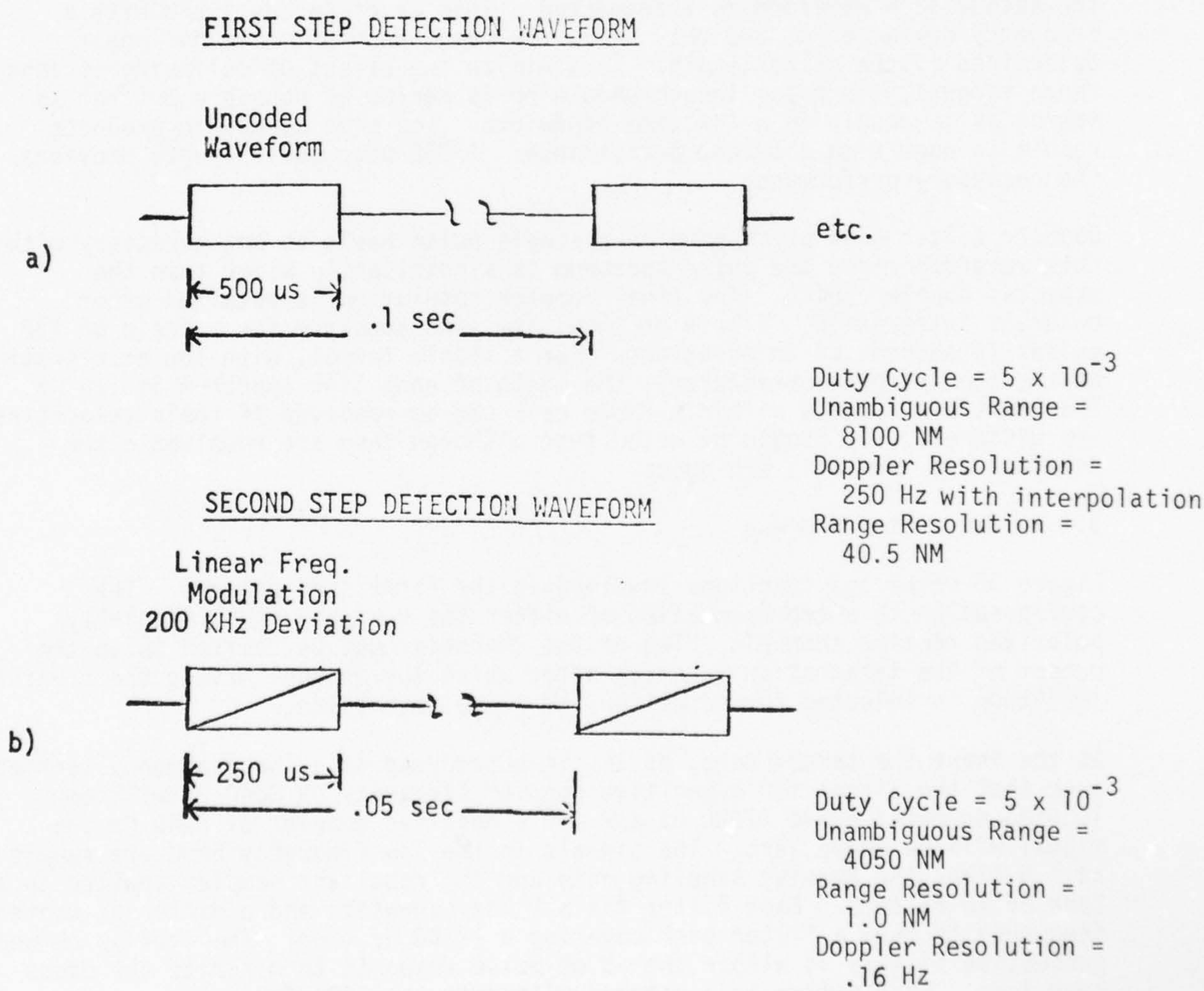


FIGURE 33. SUMMARY OF BASELINE WAVEFORMS

3.4.2.1 First Step Waveform - The first step waveform was established on the basis of using a low bandwidth waveform so that a target moving at 10,000 ft/sec would remain within a range resolution cell over a 6 second integration interval. The low bandwidth waveform is provided by using an uncoded pulse of 500 usec. The resolution of this waveform is determined by the auto correlation function shown in Figure 34a. A 10,000 ft/sec target over a 6 second integration interval will have an average loss in sensitivity due to the target motion of approximately 1.1 dB. A smaller loss can be realized by making the waveform longer. However, the range accuracy would suffer thus requiring processing of a larger range window on the second step detection process.

The spectrum of the waveform is shown in Figure 34b. At the -3.9 dB response the spectral width is 2 KHz. For target velocities of ± 10,000 ft/sec the doppler frequency is ± 8840 Hz. Thus to optimally process a single pulse a doppler filter bank (or equivalent) is used having approximately 10 filters, 2 KHz bandwidth each, covering the ± 8840 Hz band.

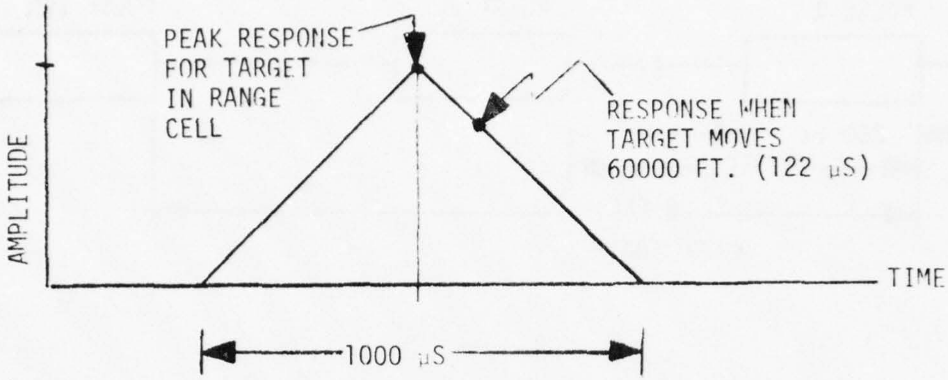
3.4.2.2 Second Step Waveform - After a detection on the first step process the second step waveform is transmitted. This waveform has a LFM with a frequency deviation of 200 KHz, hence the range resolution is no longer determined by the pulse length. To minimize the effect of eclipsing of long range targets, the pulse length should be as narrow as possible but not so narrow as to result in a low time bandwidth. Low time bandwidth products result in poor time sidelobe performance. A 250 usec pulse length provides the necessary performance.

Doppler filter bank processing on a single pulse basis is not necessary with this waveform since the pulse spectrum is significantly wider than the expected doppler shift. The final doppler resolution is obtained after coherent integration. Figure 35 shows the line spectrum for a train of 120 pulses (6 seconds of integration). For a stable target, with low acceleration during the integration interval, the width of each line spectrum is 1/6 Hz. Thus multiple targets within a range cell can be resolved if their velocities are different. It should be noted that although they are resolvable the dopplers are generally ambiguous.

3.4.3 First Step Process

Figure 36 shows the functions involved in the first step process. The configuration is a representation of either the vertical or horizontally polarized receive channels. Two of the channels must be carried up to the output of the integration function after which the channel having the greatest amplitude is selected for detection and range estimation.

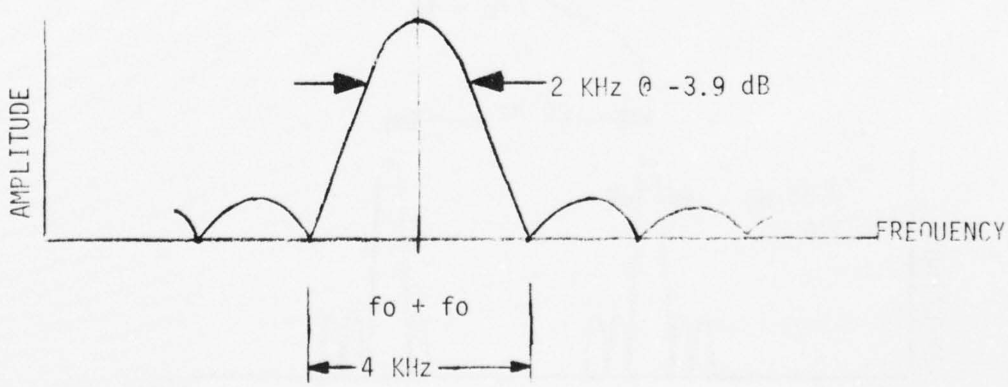
At the input the target echo, at IF, is hetrodyned to a low frequency carrier such that the signal for a positive doppler frequency of 8840 Hz will be located somewhat above 17680 Hz and for a negative doppler of 8840 Hz the signal will be above zero. The signals in the low frequency band are sampled at 1.5 times the Nyquist sampling rate and the resultant samples applied to a bank of 10 filters. Each filter has a 2 KHz bandwidth and a different center frequency to form a filter bank covering a 17680 Hz band. The overlap between successive filters is within the -3 dB pulse response to minimize the cross-over loss. Each filter is a matched filter to the 500 usec pulse.



AVERAGE LOSS DUE TO VELOCITY MISMATCH IS

$$L = \frac{1}{2}\left[1 + \left(\frac{378}{500}\right)\right] = .878 \rightarrow 1.1 \text{ dB}$$

A) AUTOCORRELATION FUNCTION



B) PULSE SPECTRUM

FIGURE 34. FIRST STEP WAVEFORM CHARACTERISTICS

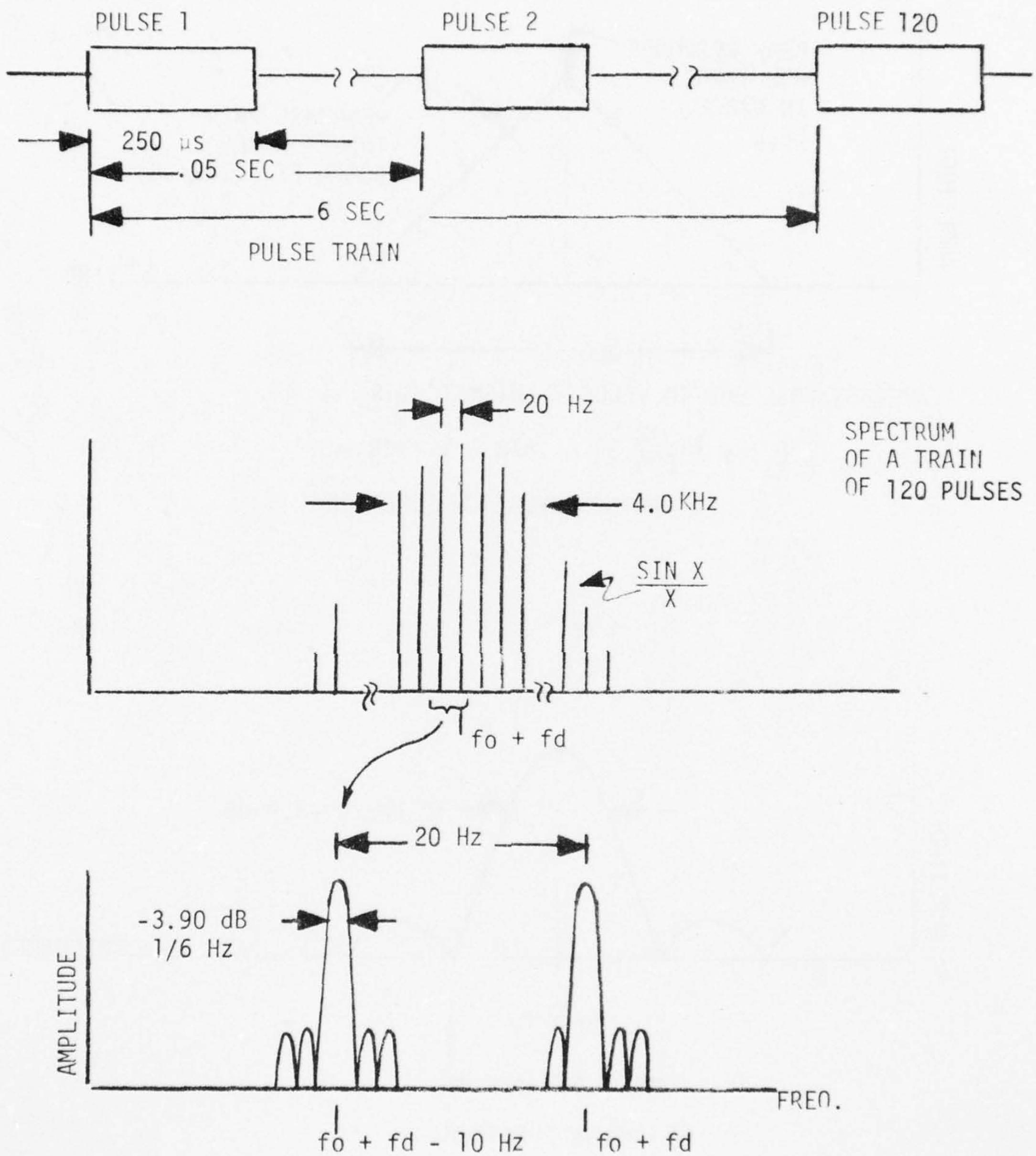


FIGURE 35. SPECTRUM OF A PULSE TRAIN

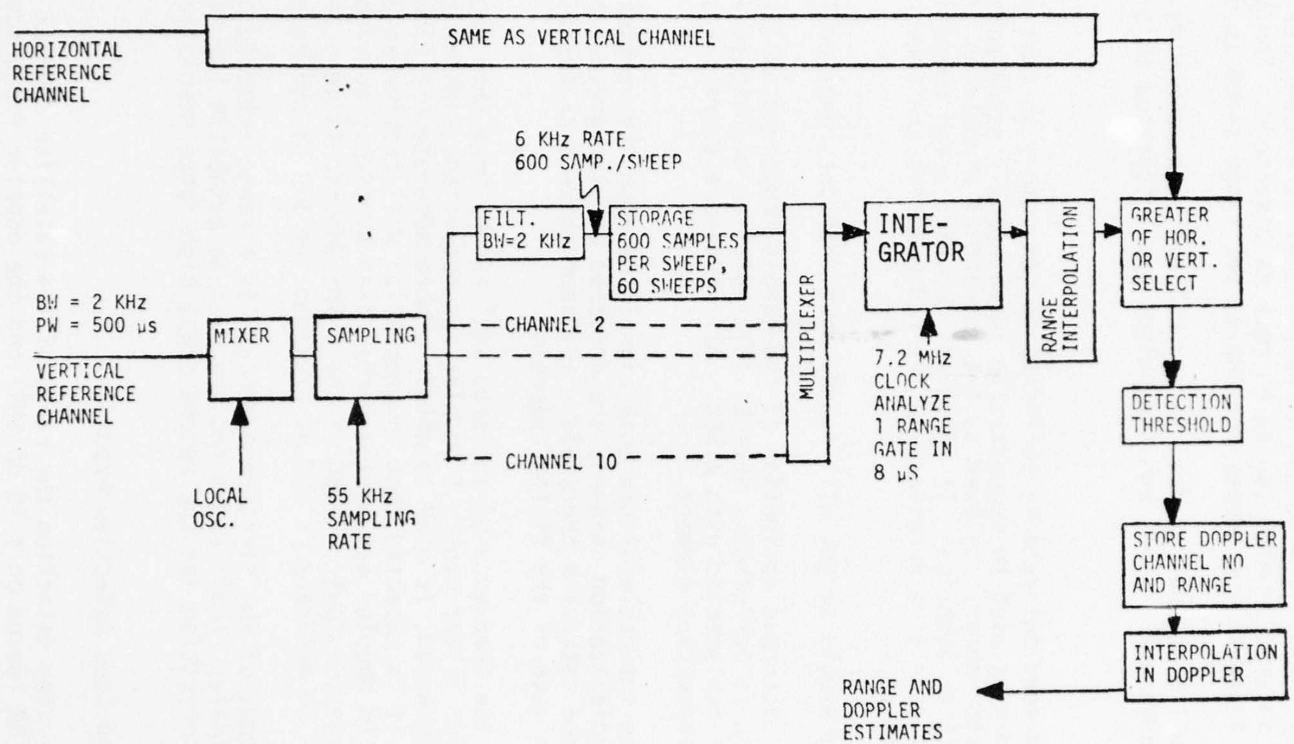


FIGURE 36. FIRST STEP DETECTION PROCESS

The entire group of samples at the filter outputs representing the range sweep is placed in storage. Although the input sample rate with each filter is 55 KHz the sample rate at the output of each filter can be reduced to approximately 6 KHz. The output of each filter is stored over the coherent integration interval, which can be as much as 6 seconds. For a .05 sec range sweep interval the number of samples per range sweep is 600.

After the full 6 seconds of data is accumulated, the memory is rapidly read out, on a range cell basis, and the pulses are integrated on a range cell basis.

A high speed read out rate is performed on the memory so that a single integrator can be used to sequentially integrate all range samples from one filter memory followed by the sequential processing of the data from the other filter memories. In addition, the high speed operation minimizes the total storage time necessary in the CCD memories and thus reduces dark current build-up.

In general a single target will occupy more than one range cell.

To obtain an accurate estimation of the target range and amplitude an interpolation is performed. Several interpolation techniques are possible which can be implemented with a CCD. All involve a short transversal filter as the key processing element.

Following the interpolator the peak signals between the vertical and horizontal polarization channels are compared and the greater of the two applied to the detection threshold. The same process as described above is performed on each of the filter channels.

In general, the frequency of the echo will occupy more than one of the filters in the doppler filter bank. A doppler interpolation, similar to that used in the range dimension, is used to obtain a more accurate estimate of the doppler frequency. It is expetted that interpolation will provide an 8 to 1 improvement in doppler estimation rather than by simply considering the filter with the largest output. Based on the 2 KHz doppler filters the interpolation will provide an accuracy of 250 Hz provided the S/N is sufficiently high.

Thus the output of the first step process is a range estimate and a coarse doppler estimate. These estimates are used to establish the range window and range walk correction for the second step, high range resolution, detection process.

3.4.4 Second Step Detection Process

On the first step detection the range of the satellite complex is determined to within 6 NM (based on a 10 dB SNR) and the doppler frequency determined to within 250 Hz ($\simeq$ 283 ft/sec). In order to resolve closely spaced targets the second step detection process uses a linear FM waveform with a 200 KHz bandwidth. Based on the range estimates made on the first step process a reduced range window ($\simeq$ 10 NM) is processed on the second step. Since the same detection sensitivity is required on the second step as was used on the first

step, the integration time on the second step is the same as on the first step. To minimize the effects of the range walk due to the higher range resolution the coarse doppler estimate obtained from the first step is used to program the movement of the range samples. In effect the range samples, over the 10 NM range window, are moved in range to match the target velocity such that the target remains within the range cell over the 6 seconds of integration time. If the uncertainty in target velocity is 250 ft/sec then in 6 seconds the differential motion between the moving range gate and the target will be 1500 feet. For a linear frequency modulated transmission, with Hamming weighting on reception, the average signal-to-noise loss due to the velocity mismatch is less than 1 dB.

The loss can be reduced by obtaining a finer estimate of doppler on the first step; this, however, is accomplished at the expense of using a lower bandwidth transmission on the first step and thereby requiring processing of a larger range window on the second step.

Figure 37 shows the functional flow diagram of the second step process. Identical channels are carried for the vertical and horizontal polarization channels. The target echo at IF is connected to its in-phase (I) and quadrature (Q) components. Each baseband channel I and Q has a bandwidth of approximately 100 KHz. The channels are sampled and applied to a pulse compression process.

Over a 6 second interval 120 range sweeps will be obtained from the pulse compression process. The 120 samples for each range cell are read out of memory and integrated in the spectrum analyzer. A range interpolation and selection of the greater of the horizontal and vertical channels is performed and the output applied to the detection threshold circuit.

The 1/6 Hz resolution of the spectrum analyzer is used for doppler resolution and the interpolated range is used as the range estimates. These estimates are used to initiate the tracking mode.

3.4.5 Baseline Processor Requirements and Implementation

Table 22 summarizes the processing requirements for the baseline system. The principal subsystem CCD implementation which is identified is: the input doppler filtering and I,Q demodulation in the first step processor, the corner turning or bulk filter requirements in first and second step, pulse compression and the coherent integrator or spectrum analyzer. These functions can be considered for both the narrow band and wideband cases and for handling the $\pm$ 10,000 ft/sec or $\pm$ 35,000 ft/sec doppler cases.

3.4.5.1 Input Doppler Filtering - The input signal handling in the first step process illustrates the option of processing signals at a low IF frequency or at baseband. Figure 38 is an implementation of the input doppler filtering with a low IF frequency sampled directly. Each doppler filter in this case consists of a pair of I and Q CCD correlators and a total of 10 filters are required. Figure 38 is an implementation requiring 20 distinct CCD filter designs. The number can be reduced to two by employing a system whereby separate mixers and reference frequency sources are used for each filter and all of the ten doppler filters are identical.

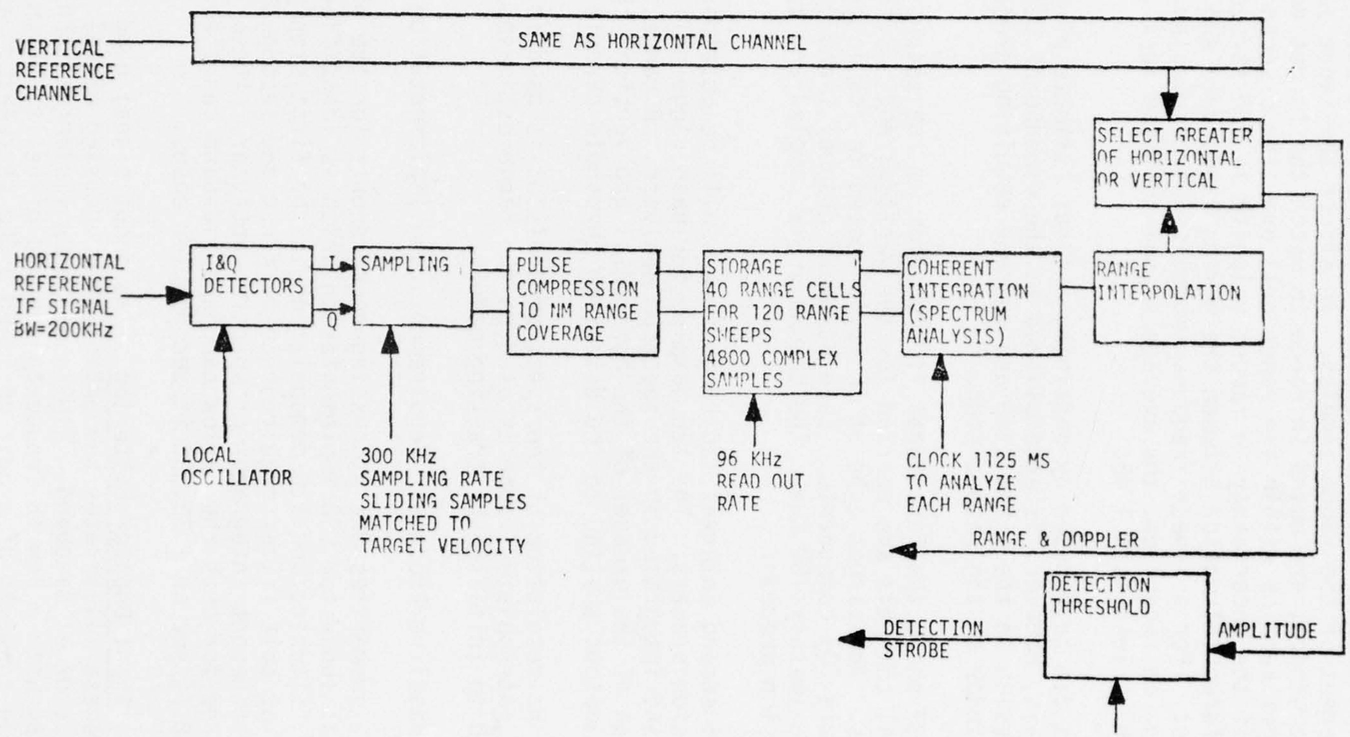


FIGURE 37. SECOND STEP DETECTION PROCESS

TABLE 22. BASELINE SUBSYSTEM REQUIREMENTS

ITEM	1ST STEP	2ND STEP
PULSE COMPRESSION	NONE	TW = 50 (LFM) W = 200 KHz
PULSES COHERENTLY INTEGRATED	60	120
INPUT SAMPLING RATE	55 KHz (IF)	300 KHz (I,Q)
DOPPLER CHANNELS	10 (INPUT)	1 (INPUT)
DOPPLER FILTER WIDTH	2 KHz	200 KHz
RANGE CELLS	600	40
SAMPLE RATE TO COHERENT INTEGRATOR (SPECTRUM ANALYZER)	7.2 MHz	96 KHz
INTERPOLATION	RANGE DOPPLER	RANGE

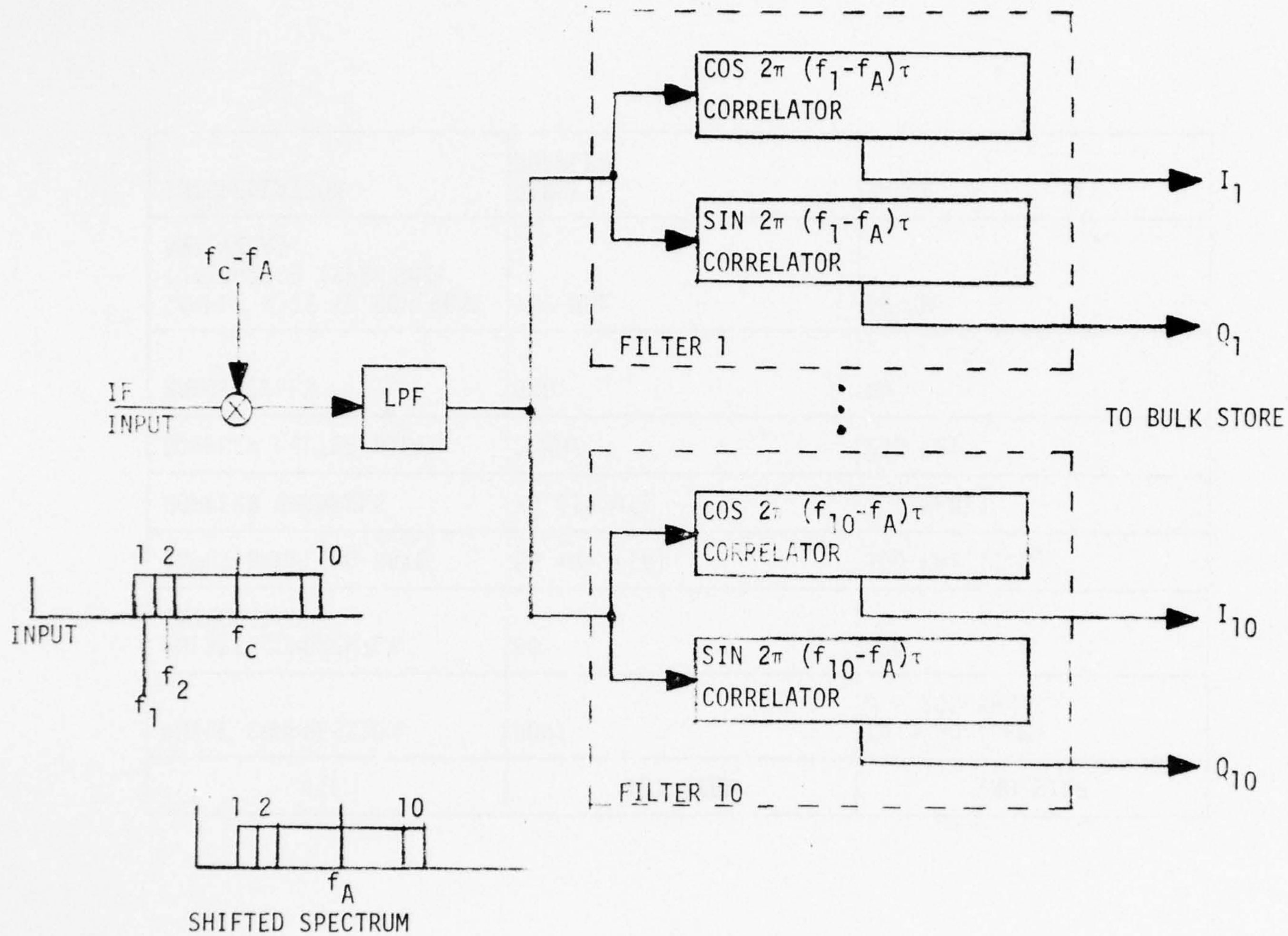


FIGURE 38. LOW FREQUENCY IF INPUT FILTERING

An I/Q baseband equivalent of the input processing is shown in Figure 39. In this case, four CCD lines are required for each doppler filter unit. However, if the ten filters are identical in shape and are symmetrically situated around the sample rate, a second filter can be realized with each unit by changing the signs of the Q summation.

Table 23 summarizes the choices for the first step input and doppler filtering. The second one was selected as the baseline approach since it offered the fewest distinct CCD designs.

3.4.5.2 Corner Turning - Bulk Memory - The requirements imposed on the bulk-corner turning memory by the various system options are listed in Table 24. Although the maximum storage time listed is 6 seconds, as noted in Section 3.2, system requirements for very long range detection could impose times of 12 seconds or more. The length of storage time is the most critical requirement from the point of view of the basic CCD physics and as shown in Section 6.0, it can only be achieved if the devices are cooled. Either input or output multiplexing as described in Section 3.3 is a satisfactory approach for the corner turning memory.

3.4.5.3 Pulse Compression - The low bandwidth pulse compression requirement with a time-bandwidth product of 200 can be met with a straightforward implementation of a transversal matched filter with four elements as discussed in Section 3.3. However, for the long TW products three alternates are possible; the step transform, a sub-aperture CZT approach giving a large DFT-DFT^{-1} matched filter and a sub-aperture convolver with minimum range. The CCD hardware impact of these alternatives are tabulated in Table 25. The step transform approach is most attractive in this case because it minimizes the size and number of the CCD's relative to the sub-aperture CZT and avoids the requirement for programmability as in the case of the sub-aperture convolver. Full range search is an additional advantage.

3.4.5.4 Coherent Integration - The coherent integration alternatives are listed in Table 26. A chirp-Z transform implementation is optimum at this point because of the well developed split-gate tap weight technique. As the methods of parallel data transfer and switching control on CCD's are improved, further performance advances in CZT's and stored coefficient analyzers will ensue.

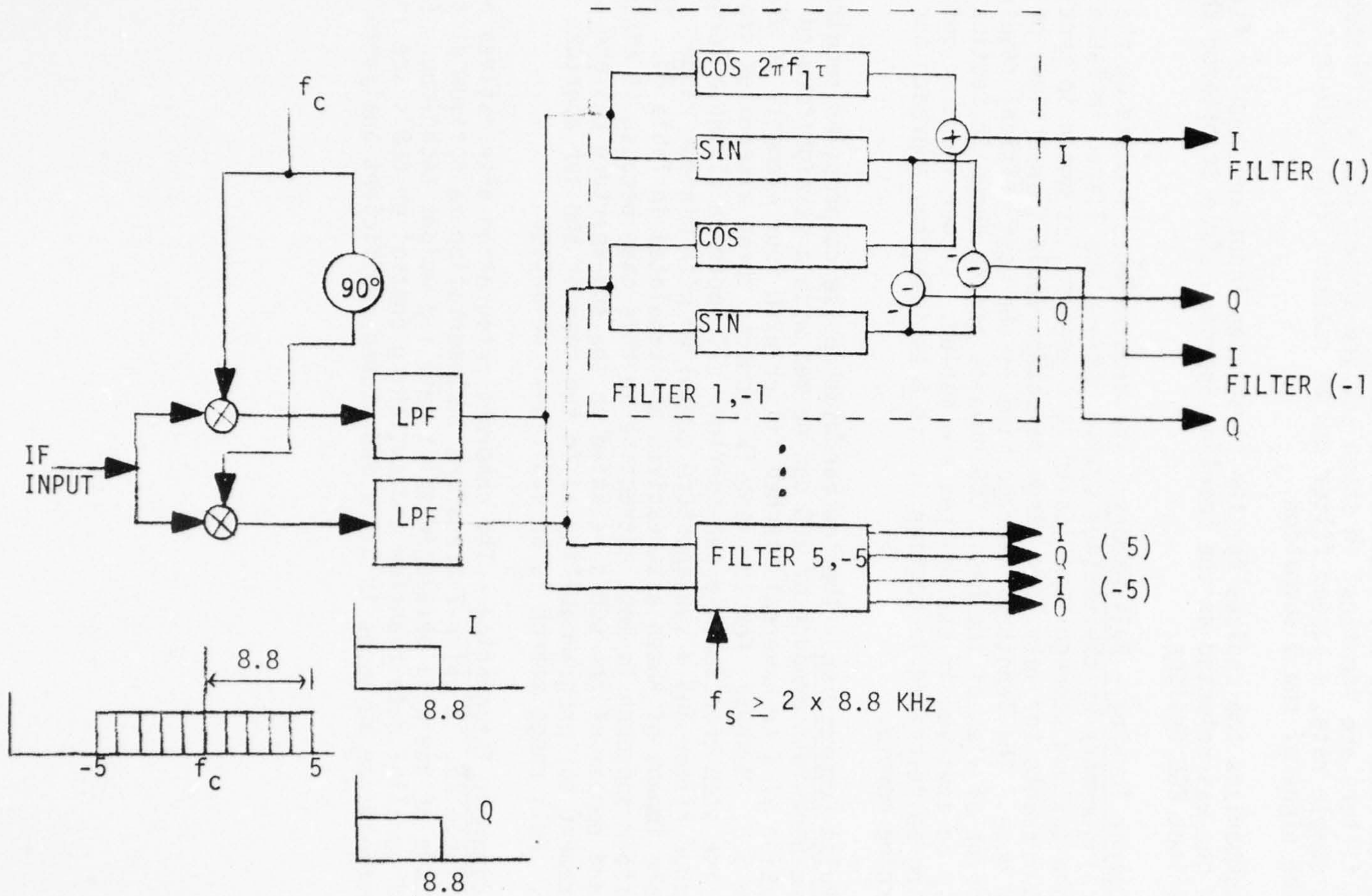


FIGURE 39. I/Q BASEBAND SAMPLING WITH I/Q FILTERS

TABLE 23. FIRST STEP INPUT AND DOPPLER FILTERING

	INPUT PROCESS			DOPPLER FILTERS			
TYPE	MAX. VELOCITY FT/SEC	SAMPLE RATE (KHz)	FREQ. SOURCES	TOTAL CCD UNITS	CCD FILTER DESIGNS	NO. OF TAPS	REMARKS
LOW FREQ. IF INPUT	10,000	5.5	1	40	20	28	° SIMPLEST INPUT PROCESSING ° MOST FILTER DESIGNS
	35,000	19.3	1	140	20	97	
FIXED DOPPLER LOW FREQ. IF INPUT	10,000	5.5	10	40	2	28	° MINIMUM FILTER DESIGNS ° REQUIRES FREQUENCY SYNTHESIZER
	35,000	19.3	10	140	2	97	
I/Q DEMODULATION	10,000	26.5	1	40	10	14	° LOWEST SAMPLE RATE ° SMALLEST CCD FILTERS
	35,000	92.8	1	140	10	40	

TABLE 24. BULK MEMORY REQUIREMENTS

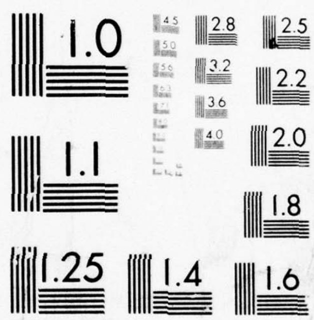
CASE		NUMBER OF UNITS	ORGAN-IZATION (FUNCTION)	SAMPLES PER UNIT	TOTAL SAMPLES	MAXIMUM STORAGE TIME	MAXIMUM SAMPLE RATES (KHz)	
							INPUT	OUTPUT
FIRST STEP	MAX VELOCITY =10,000 FT/SEC	40	CORNER TURNING (60x600)	36,000	1.44×10^6	~6 SEC	5.5	7200
	MAX VELOCITY =35,000 FT/SEC	140	CORNER TURNING (60x600)	36,000	5.04×10^6	~6 SEC	19.3	7200
SECOND STEP	200 KHz BW	4	CORNER TURNING 40x120	4,800	19,200	~6 SEC	300	100
	5.0 MHz BW	4	CORNER TURNING 1000x120	120,000	480,000	~6 SEC	7500	2500

TABLE 25. CCD PARAMETERS FOR TW = 10,000 PULSE COMPRESSION ALTERNATIVES

TECHNIQUE	CCD FILTERS		CCD DELAYS		CLOCK RATE	RANGE COVERAGE
	LENGTH	NUMBER	SAMPLES	NUMBER		
STEP TRANSFORM	200	16	2-6000	60	7.4 MHz	FULL RANGE SEARCH
SUB-APERTURE CZT TRANSFORM	1000	192	1000-23,000	46	12 MHz	FULL RANGE SEARCH
	24	192				
SUB-APERTURE CONVOLUTION	1000 (PROGRAM-MABLE)	20	1000-4000	8	6 MHz	44 NM

AD-A051 333 RCA GOVERNMENT SYSTEMS DIV MOORESTOWN N J MISSILE AND--ETC F/G 17/9
CCD SIGNAL PROCESSOR STUDY.(U)
DEC 77 L W MARTINSON, B P GAFFNEY, G J MAYER F30602-76-C-0280
UNCLASSIFIED RADC-TR-77-422 NL

2 OF 4
AD
A051 333



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 26. COHERENT INTEGRATION ALTERNATIVES

REQUIREMENTS:

INPUT SAMPLE RATE: UP TO 7.2 MHz
APERTURE SIZE: 23, 60, 120 SAMPLES

ALTERNATIVE	CCD LINE LENGTH FOR 120 SAMPLES	CCD CLOCK RATE	SPECIAL CCD REQUIREMENTS
CHIRP-Z FILTER	120 FILTER, 120 DELAY	3 TIMES REAL TIME INPUT RATE	
STORED COEFFICIENT	120	REAL TIME INPUT RATE	° SERIAL-PARALLEL BUFFER ° N x N COEFFICIENT STORAGE MULT. ° ANALOG MULTIPLIER ON CHIP
DELTIC	120	120 TIMES REAL TIME INPUT	LOW TRANSFER LOSS DUE TO RE-CIRCULATION (DELAY ONLY)

4.0. CCD CHARACTERISTICS

4.1 CCD OPERATING PRINCIPLES*

4.1.1 Background

In 1970, W. S. Boyle and G. E. Smith of Bell Laboratories, reported the concept of semiconductor charge coupled devices (CCD's).[5] Since that time, progress in CCD development has been rapid. The technology has advanced from laboratory demonstration of eight-stage CCD delay lines, which lost 1-2 percent of the stored charge with every transfer [6], to 500-800 stage CCD delay line/transversal filters, which lose .01-.02 percent with every transfer.[7 ,8] As CCD performance has increased, so also have device design variations.

The characteristics by which CCD's are characterized include:

- ° Surface or Buried Channel.
- ° The Number of Clock Phases (Three, Two, and One-Phase).
- ° Various Input/Output Techniques.
- ° Clock Swing Voltages.
- ° Gate Areas.

All of the above characteristics directly affect device performance. In addition, any CCD can be operated with different parameters that alter device performance. An example is the percent of input background charge which directly affects the charge transfer efficiency. The large variation in CCD operating conditions have made many performance reports in the literature difficult to correlate, usually due to the lack of complete experimental descriptions. It is apparent, however, that certain CCD designs and operating conditions are becoming typical of good operation.

In order to realistically describe CCD performance, the theoretical considerations will be presented along with typical operating conditions. The CCD as a delay line and as a tapped delay line has been modeled and a computer simulation described in Section 5.0 has been developed. A substantial amount of literature has been generated describing CCD operation and performance, with much of it containing sophisticated analyses. These analyses lead to CCD performance predictions with first, second, and higher order effects. The scope of the computer simulation of this program incorporates first and second order effects of the predominate CCD variables. Higher order effects were not included since their impact on CCD performance was minimal.

Many references were consulted in the development and verification of the CCD model. Internal RCA laboratory measurements were also used as a validation of the model and the computer simulation. Limitations of the model and simulation will be noted where they apply.

4.1.2 Basic CCD Operation

An analog signal connected to the CCD input is sampled and a charge packet is generated by the input structure. The magnitude of this charge packet is

* A glossary of CCD terms is provided at the end of this section.

proportional to the analog signal sample. The charge packet is attracted to the region with the minimum potential energy. This region, called potential well, occurs under an MOS gate when a voltage is applied to the gate. A linear array of closely spaced MOS gates with properly controlled adjacent gate voltages allows the charge packet to be transferred down the gate array. When the charge packet has been transferred through the entire gate array, its magnitude is sensed by the output structure.

Referring to Figure 40, when two adjacent transfer gates have the same voltage applied, the charge packet will be equally distributed under the two (Time 1). When the voltage is removed from one gate, the charge packet will be distributed under the second transfer gate (Time 2). The process is repeated (Time 3 and 4) until the charge packet resides under the desired transfer gate. In this example, three gates are used to provide direction to the transfer. This shows that a three or higher-phase clock system can be used to control charge transfer. A two-phase clock system can be used if direction is built into the clock structure. This is shown in Figure 41 with the aid of a potential profile line.

The first and second gates are connected to the same phase clock with the first gate voltage reduced by ΔV. Gates three and four are connected in a like manner. The ΔV bias gives direction to the charge transfer. One stage of a three-phase clock CCD consists of three gates which involves three transfers. One stage of a two-phase clock CCD consists of four gates with two transfers. Charge is not stored under the first or third gates, but under the second and fourth. The clock frequency and the number of stages determines the time delay of the CCD.

There are many CCD input and output techniques that have been published.[9, 10] A given input structure can be operated in different ways to inject charge into the CCD, but each method operates by generating charge and forming charge packets. Some input structures are more linear than others, while some allow larger charge packets to be formed, or are less noisy. CCD output techniques operate by detecting the change of charge present in the output structure. As in the input, linearity, signal amplitude and noise are factors that must be considered.[9]

4.1.3 Physical Description

CCD's are solid-state devices usually constructed on silicon substrates. They can be fabricated using standard MOS processing. A cross-section of a surface-channel CCD is shown in Figure 42. The charge transferred down the CCD physically resides at the S_i-S_iO_2 interface. A buried-channel CCD is shown in Figure 43.

A buried-channel CCD uses an epitaxial or ion-implanted silicon layer (N-layer) of polarity opposite to that of the substrate (P-substrate). This layer shifts the transferred charge away from the S_i-S_iO_2 interface into the bulk of the N-layer material.

The charge packets are contained under specific transfer gates by the appropriate gate voltages. The charge packets are prevented from being

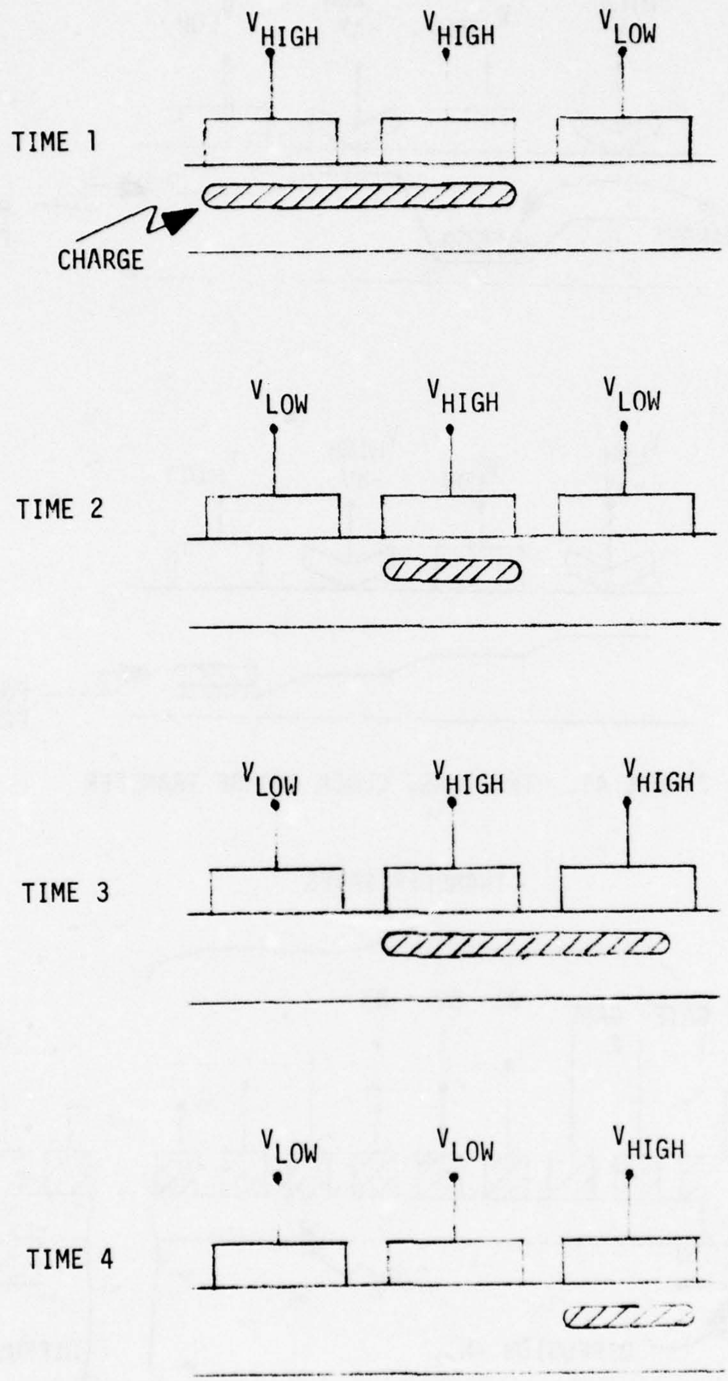


FIGURE 40. CHARGE TRANSFER

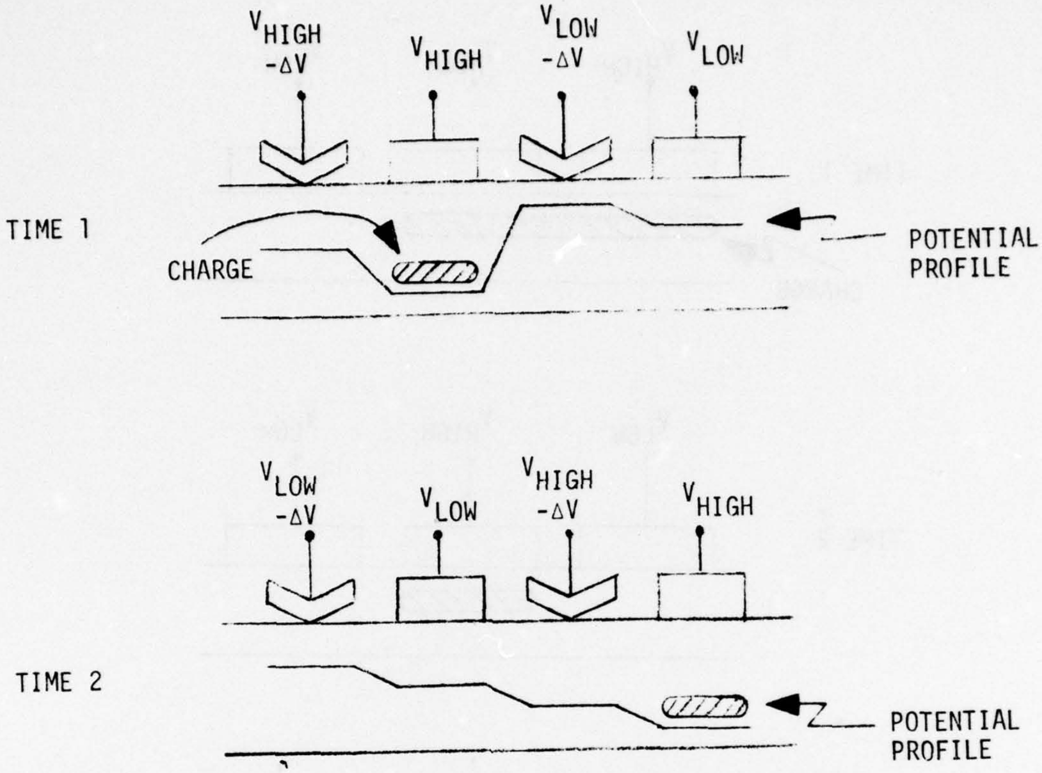


FIGURE 41. TWO-PHASE CLOCK CHARGE TRANSFER

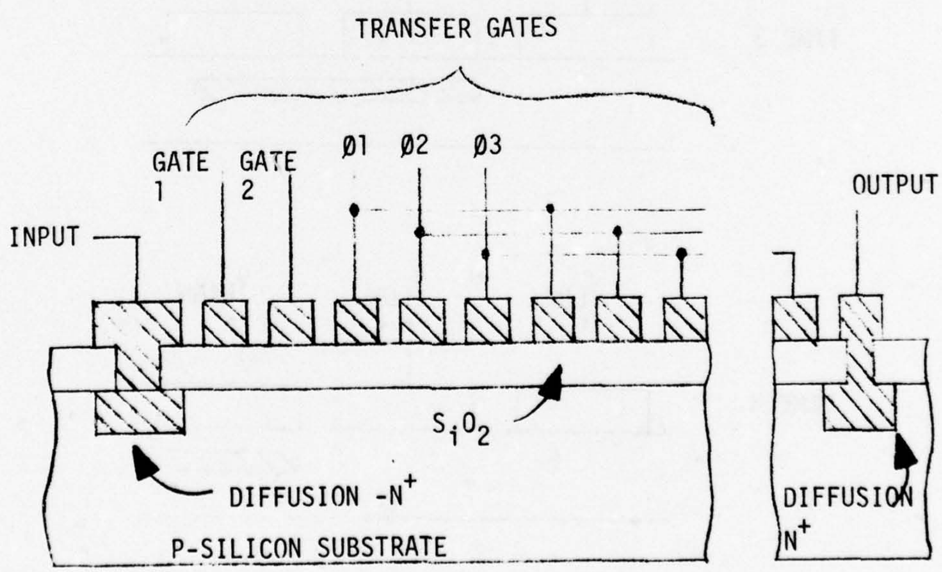


FIGURE 42. CROSS SECTION OF SURFACE CHANNEL CCD

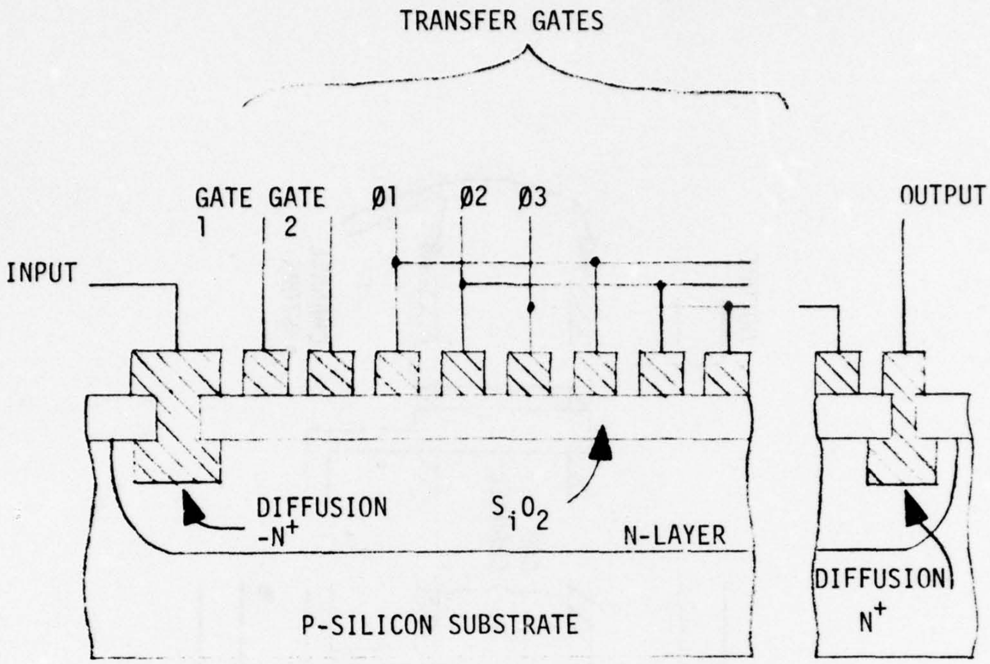


FIGURE 43. CROSS SECTION OF BURIED CHANNEL CCD

laterally dispersed by channel stops shown in Figure 44 which define the CCD channel. In addition to confining the charge packets, the channel stops also keep the charge packets physically separated from the clock bus lines.

The input structure consists of the input diffusion and gates 1 and 2 of Figures 42 and 43. Input structures can also be constructed with an input diffusion and only gate 1 or, as an additional variation, it can contain an additional gate (Gate 3). The output structure shown in Figures 42 and 43 consists simply of the output diffusion. A variety of output structures exist, however, the split-gate structure is described since it is an important technique in the fabrication of a tapped CCD delay line.

The transfer gates can be used to sense the charge passing beneath them as well as causing the charge to transfer. In order to implement a weighted tapped delay line, transfer gates can be split as shown in Figure 45.

The phase three (Ø3) gates are shown split into $Ø3^+$ and $Ø3^-$. The amount of charge detected by a given split gate depends directly on its area. The charge packet proportional to the input signal sample is equally distributed across the CCD channel. Therefore, the charge packet under the split gate is weighted by the relative area of the $Ø3^+$ gate to the $Ø3^-$ gate. The Ø3 clock bus lines act here as summers for the plus contributions and for the minus contributions. The plus and minus buses are then applied to the appropriate inputs of a differential amplifier. If the split of a particular gate occurs at the middle, the corresponding weight at that gate is zero. If the split occurs closer to the minus side of the CCD channel, the weight will be positive for that gate. An analog weight from +1 to -1 can thus be obtained.

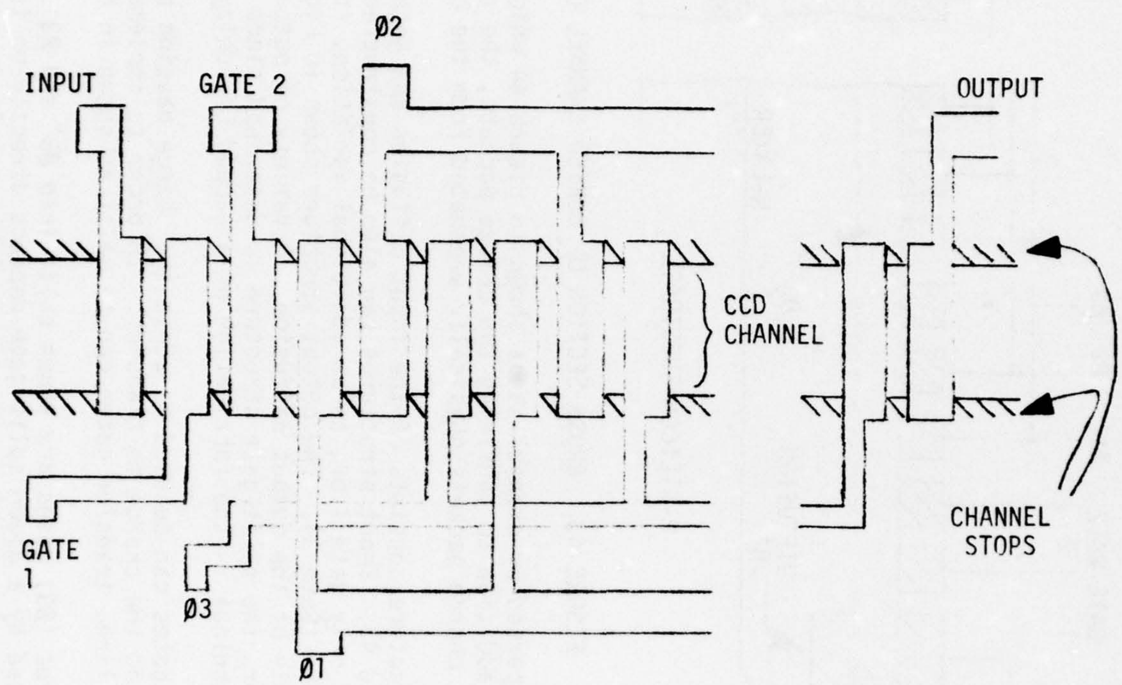


FIGURE 44. CCD (TOP VIEW)

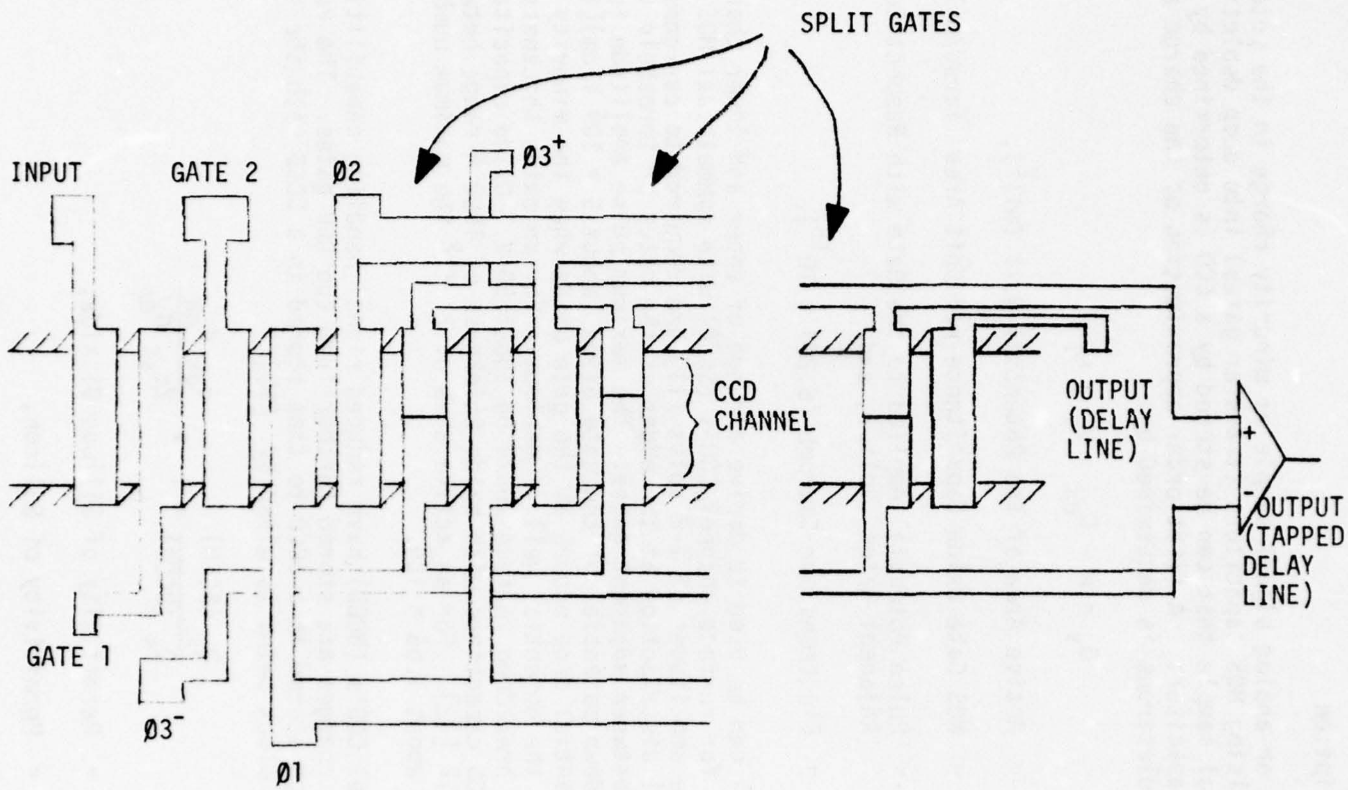


FIGURE 45. SPLIT-GATE CCD

4.2 SIGNAL SAMPLE STORAGE

4.2.1 Description

A CCD stores an analog signal sample as minority charge in the potential wells formed by pulsing MOS capacitors (transfer gates) into deep depletion. The maximum signal sample that can be stored by a CCD is determined by the size of the MOS capacitors. A first order approximation of the charge stores (Q_s) measured in electrons is determined by:

$$Q_s = A \cdot C_{ox} \cdot V_p \cdot K_1 \qquad (1\ )$$

where: A = Active Area of the Potential Well (mil^2),

C_{ox} = MOS Gate Oxide Capacitance per Unit Area ($farad/mil^2$),

V_p = Pulse Potential Applied to the Gate with Respect to the Adjacent Gates (Volts), and

K_1 = Electrons per Coulomb ($6.284 * 10^{18}$).

Equation (1) can be used to derive a range of upper and lower charge handling capabilities for surface channel CCD's (SCCD) with symmetrical MOS gates. Minimum pulse amplitudes of 1-2 volts [11] are required to overcome anomalies in the potential distribution at the edges of the gates or threshold voltage differences between adjacent gates. The maximum pulse amplitude is determined by the breakdown potential of the gate oxide (about $5 * 10^6$ V/cm)[11] because the main potential drop occurs at the gate oxide when the minority charge contained in the potential well is maximum. For an oxide thickness of 1000 Å (100 nm) the breakdown voltage would be about 50 V. Oxide capacitance (C_{ox}) levels for MOS capacitors with oxide thickness of 1000 Å range between .225 and .3 pf/mil^2 [12]. For an active area of 2 mil^2 the maximum number of electrons is about $1.65 * 10^8$.

Buried channel CCD's (BCCD) have reduced signal handling capabilities since the minority charges are stored further from the CCD gates. The ratio of maximum charge stored in a SCCD to that stored in a BCCD with the same gate geometry and clock swing is given by: [10]

$$\frac{Q_s\ (SCCD)}{Q_s\ (BCCD)} = 1 + \frac{\varepsilon_{ox}\, d_{ch}}{2\varepsilon_{si}\, d_{ox}} \qquad (\ 2)$$

where: ε_{ox} = Permitivity of Silicon Dioxide,

ε_{si} = Permitivity of Silicon,

d_{ch} = Effective Thickness of Channel Implant, and

d_{ox} = Oxide Thickness.

For a device with d_{ox} = .1 μm and d_{ch} = .6 μm the ratio Q_s (SCCD)/Q_s (BCCD) is about 2. Thus a BCCD has approximately one-half the number of electrons in a full well as a similar SCCD.

4.2.2 Typical Parameters

Although the charge storage per potential well increases as the voltage applied to the transfer gate, most CCD's are not driven with the maximum level of 50 volts, but with voltages between 9-15 volts. This is primarily due to power dissipation limitations in the CCD clock drivers. The CCD gates appear as large capacitances; therefore, the power to drive the clock gates is mainly reactive. The power is dissipated in the driver according to:

$$P = f_c \cdot C \cdot V_p^2 \qquad (3)$$

where: f_c = Clock Frequency,

C = Gate Capacitance, and

V_p = Pulse Potential Applied to the Gate.

The power increases with the square of the drive voltage and for high frequency operation (>1 MHz) commercial switch-transistor integrated circuits reach their power dissipation limit at drive voltages around 10-15 volts.

Typical SCCD full potential wells hold a maximum of 3.29 * 10^7 electrons at 9 volts to 4.95 * 10^7 electrons at 15 volts for a 2 mil^2 gate area. Typical BCCD potential wells would hold about half that number of electrons (1.64 * 10^7 - 2.47 * 10^7 electrons).

Gate area is the product of the gate length and the channel width. Most CCD's have been built with gate areas between .32 and 3.2 mil^2. However, it is feasible to construct dense CCD's, with gate areas as low as .02 mil^2; and future predictions of .01 mil^2 have been made.[14] Gate areas larger than 4 mil^2 can be built for applications requiring large charge storage capability such as accumulators.

Oxide capacitance per unit area depends on the thickness and permitivity of the oxide as follows:[12]

$$C_{ox} = 8.85 * 10^{-10} \frac{\varepsilon_{ox}}{d_{ox}} \frac{pf}{\mu^2} \qquad (4)$$

where ε_{ox} is between 2.7 and 4.2.

Oxide Thickness d_{ox} (Å)	Oxide Capacitance, C_{ox} (pf/mil^2)
1000	.225 - .30
1500	.150 - .20
2000	.112 - .15

According to Equation (1), the amount of stored charge increases as the oxide capacitance per unit area and the oxide thickness should therefore be minimized for maximum charge storage. For oxide thickness less than 1000 A pinhole failure modes begin to reduce the yield of fully operational CCD's.

4.2.3 Simulation - Model

Electrons are the common variable for all the CCD factors considered. The maximum number of electrons a potential well can hold (a full well) sets the largest signal sample amplitude that can be input to the CCD. The full well electrons (Q_S) determined by Equation (1) and the following parameters:

A = Simulation Parameter Input (mil^2)

C_{ox} = .262 (pf/mil^2) for 1000 Å Thick Oxide

V_p = Simulation Parameter Input (Volts)

K_1 = $6.28 * 10^{18}$

SCCD or BCCD = Simulation Parameter Input (Q_s (BCCD) = 1/2 Q_s (SCCD))

Shown below are the number of electrons for a full well as calculated by the simulation.

TYPE	GATE AREA (mil^2)	CLOCK VOLTAGE (Volts)	FULL WELL ELECTRONS
SCCD	2	10	$3.29 * 10^7$
SCCD	2	15	$4.94 * 10^7$
SCCD	4	10	$6.59 * 10^7$
SCCD	4	15	$9.89 * 10^7$
SCCD	.3	10	$4.95 * 10^6$
SCCD	.02	10	$3.29 * 10^5$
SCCD	.01	10	$1.65 * 10^5$
BCCD	2	10	$1.64 * 10^7$
BCCD	2	15	$2.47 * 10^7$
BCCD	4	10	$3.29 * 10^7$
BCCD	4	15	$4.94 * 10^7$
BCCD	.3	10	$2.47 * 10^6$
BCCD	.02	10	$1.65 * 10^5$
BCCD	.01	10	$8.24 * 10^4$

4.3 TRANSFER EFFICIENCY AND BACKGROUND CHARGE

4.3.1 Description

When the charge packet is transferred from one potential well to the next, a small fraction of the charge packet is left behind. Two mechanisms contribute to this charge transfer inefficiency (CTI), free charge transfer and signal charge interaction with traps. The trapping is due to interface state and bulk traps in SCCD's and bulk traps only in BCCD's.

Free charge transfer is the process that describes the movement of charge from one potential well to the next. The amount of charge transferred is time dependent. If the time allowed for charge transfer is too short, not all of the charge will be transferred. The trapped charge will either be forced backward or into the substrate where it is lost. The speed and amount of charge transferred strongly depends upon the CCD gate length and substrate doping. Keeping the substrate doping less than 10^{15} cm^{-3} and gate length less than 10 microns gives a charge transfer efficiency (CTE) of 99.99% for clock frequencies greater than 10 MHz considering the effects of free charge transfer only.[15] Therefore, keeping these design considerations in mind, CTI can be considered independent of frequency for most CCD applications.

The effect of traps (interface state and bulk) is independent of frequency. SCCD's are primarily affected by interface state traps as most of the signal charge resides in about 10 nm of the interface. In BCCD's, the signal charge resides entirely in the bulk. Empty traps capture signal charge as it comes in contact with them in less than 1 ns. Full traps release this signal charge at a much slower rate. This results in a smearing of the input signal. BCCD's experience less CTI from traps than SCCD's because the bulk traps are less dense than the interface state traps.

In order to reduce the CTI, it is common practice to continuously input an amount of charge which will fill up the traps. This allows the signal charge to transfer down the CCD and not encounter any empty traps. This background bias charge is referred to as "fat zero" in SCCD's and "slim zero" in BCCD's. The amount of fat or slim zero is given in % of the full well electrons.

The use of fat or slim zero reduces the number of full well electrons that can be used for signal charge. To obtain the best CTE from a CCD some reduction in the input signal sample range must be made.

4.3.2 Typical Parameters

SCCD's typically require about 10-15% fat zero to fill the interface state traps. The number of electrons required to fill the bulk traps is less and therefore the slim zero level for BCCD's is usually between 5% and 10%. The relationship of fat or slim zero to CTE depends on the device. The range of fat (10-15%) and slim (5-10%) zero given above was obtained from the published literature. The corresponding levels given for CTE are 0.9999 for SCCD's and 0.99999 for BCCD's.

Since charge transfer efficiency is a function of background charge, it is desirable to obtain a functional relationship between the two. The fraction

of signal lost in passing through a CCD as a function of background charge for SCCD's and BCCD's has been measured.[16] The fraction of signal lost is related to charge transfer inefficiency (CTI) as follows:

$$\text{CTI} = \frac{\text{Fraction of Signal Lost in CCD}}{\text{Number of Transfers}} \quad (5)$$

For Tompsett's results, the number of transfers is 256 stages x 3 phases per stage or 768. Figure 46 shows the measured results and the linear piecewise approximation made. The expressions used for the linear approximation are shown below.

SCCD

Section of Curve	Background Charge (%)	Signal Fraction Lost (%)	CTI
A	0-4	28	$3.6 * 10^{-4}$
B	4-5	-21x + 112	$-2.7 * 10^{-4} + 1.4 * 10^{-3}$
C	5-10	-.8x + 11	$-1.0 * 10^{-5} + 1.4 * 10^{-4}$
D	10 →	3	$3.9 * 10^{-5}$

(Background charge ranges A–D: X)

BCCD

Section of Curve	Background Charge (%)	Signal Fraction Lost (%)	CTI
E	0-4	-1.25x + 8.9	$-1.6 * 10^{-5} + 1.1 * 10^{-4}$
F	4-13.5	-.16x + 4.5	$-2.1 * 10^{-6} + 5.8 * 10^{-5}$
G	13.5 →	2.2	$2.8 * 10^{-5}$

(Background charge ranges E–G: X)

Tompsett's results give a good indication of the CTI/background charge relationship. However, his results are not definitive. A fat zero of 10% for a SCCD gave the same CTE as a slim zero of 7% for a BCCD; CTE = .999961. These results are good for a SCCD, but poor for a BCCD.

4.3.3 Simulation - Model

The simulated device is a two-phase CCD, as shown in Figure 41. The second and fourth gates in each stage function are the storage gates. The first and third gates act as barriers to prevent the backward flow of charge. Due to the gate functions, only the second and fourth gates need to be simulated as long as the charge transfer direction is correct. The simulation has the device type specified (SCCD or BCCD) as indicated in Section 4.2.3. The simulation gives the option of either specifying the CTI as a parameter or by specifying a percent of background bias charge which then computes the CTI. Typical values for CTI as a function of background charge percentage derived from the linear approximation in Figure 46 are given in Table 27.

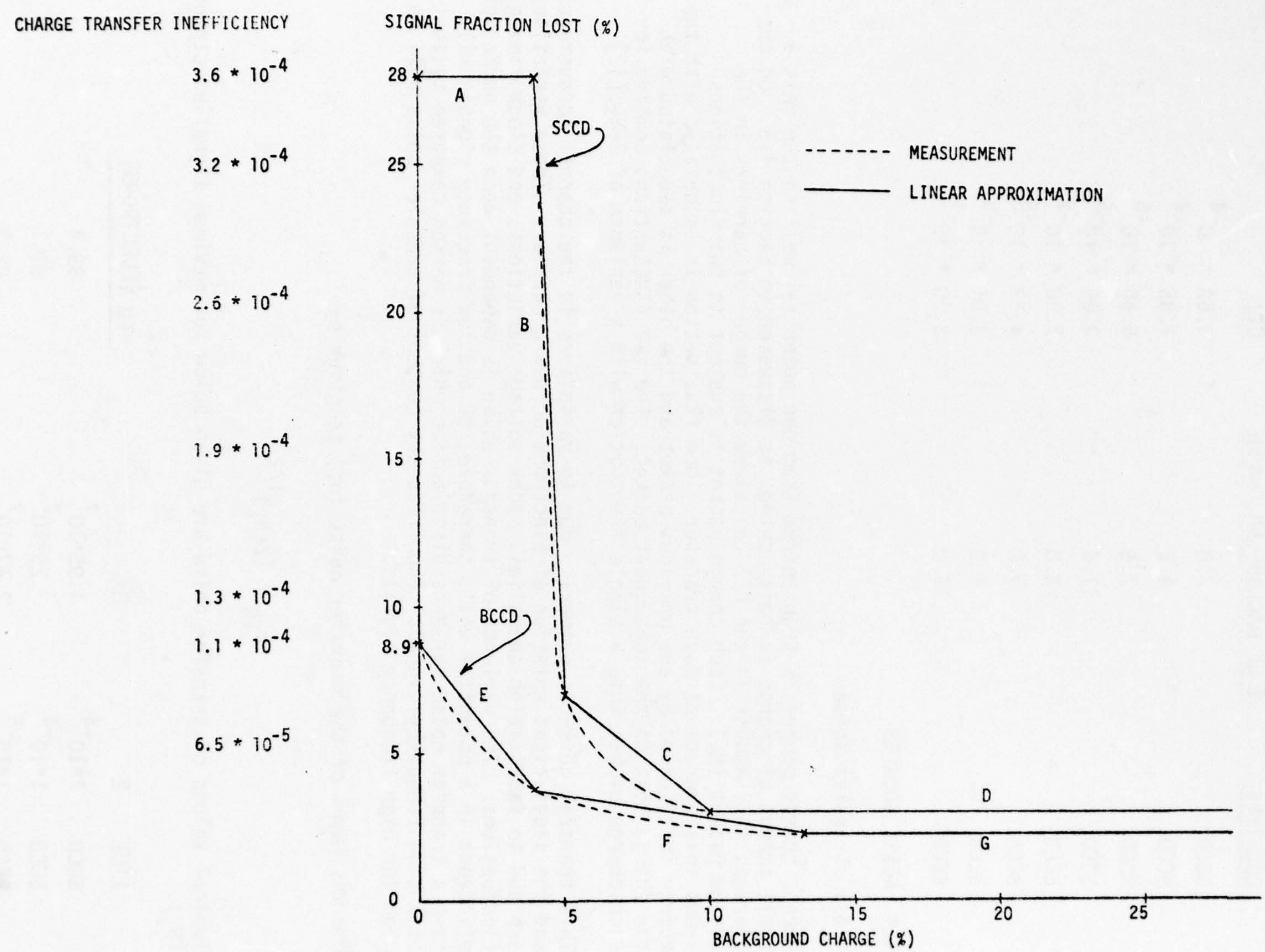


FIGURE 46. CHARGE TRANSFER INEFFICIENCY VERSUS BACKGROUND CHARGE

TABLE 27. TYPICAL VALUES OF CTI

CCD TYPE	% OF BACKGROUND CHARGE	CTI
SCCD	2.0	$3.60 * 10^{-4}$
SCCD	4.5	$1.85 * 10^{-4}$
SCCD	7.5	$6.50 * 10^{-5}$
SCCD	11.0	$3.89 * 10^{-5}$
BCCD	2.0	$7.80 * 10^{-5}$
BCCD	7.0	$4.33 * 10^{-5}$
BCCD	9.0	$3.91 * 10^{-5}$
BCCD	14.0	$2.80 * 10^{-5}$

4.4 NOISE SOURCES

4.4.1 Transfer Noise

When a charge packet is transferred from one potential well to the next a small amount of charge is left behind, as discussed in Section 4.3. On the average, this amount is the CTI (e) times the number of carriers in the charge packet (N_S). Each charge packet is subject to two fluctuations about this average at each transfer. One fluctuation is associated with the charge left behind by the previous packet and the other is associated with the charge lost to the subsequent packet. The two fluctuations combine for each charge packet into a single fluctuation with a variance of $2eN_S$.[17]

This transfer noise is primarily due to variations in the channel conductance and the statistical emission of electrons across a barrier. These variations are due to fabrication anomalies, clock voltage variations, and clock timing fluctuations. The variance of transfer noise is dependent upon the number of electrons in a potential well; therefore, DC and low frequency signals will have a transfer noise variance distribution which is narrow compared to that of a high frequency signal. The frequency content of transfer noise will be high for high frequency signals.

The RMS level of the transfer noise (σ_T) is given by:

$$\sigma_{TR} = (2eN_s)^{1/2}$$

Typical values of transfer noise are given below for maximum signal electrons (N_s).

TYPE	e	N_S	σ_{TR} (ELECTRONS)
SCCD	$1*10^{-4}$	$4.95*10^{7}$	99.4
SCCD	$1*10^{-4}$	$3.29*10^{7}$	81.1
BCCD	$1*10^{-5}$	$2.47*10^{7}$	22.2
BCCD	$1*10^{-5}$	$1.64*10^{7}$	18.1

4.4.2 Thermal Shot Noise

Since a CCD is normally operated in deep depletion, there is a thermal generation of electrons which will re-establish an equilibrium condition. These electrons generated as a function of time are referred to as "dark current". There is an average dark current with spatial variations described in Section 4.5. Associated with this is a thermal shot noise with a variance, σ_{SN}^2, of:[18]

$$\sigma_{SN}^2 = \frac{J_D A K_2}{q f_c} \qquad (6)$$

where: J_D = Dark Current Density (A/cm^2)

A = Area of Potential Well (cm^2)

q = Electron Charge (Faraday)

f_c = Clock Frequency (H_z)

K_2 = $(1.0363*10^{-5})$

Thermal shot noise is completely uncorrelated from charge packet to charge packet and this results in a white frequency spectrum. The thermal shot noise variance increases as temperature due to the dark current density (J_D) increase with temperature. Substituting the following parameters in Equation (6):

$J_D = 2*10^{-9}\ A/cm^2$

$A = 1.29*10^{-5}\ cm^2\ (2\ mil^2)$

$K_2 = 1.0363*10^{-5}$

$q = 1.64*10^{-24}$ Faraday

we obtain the following values for σ_{SN} in electrons.

f_c (Hz)	σ_{SN} (ELECTRONS)
1,000	12.7
10,000	4.0
100,000	1.3

4.4.3 Trap Noise

SCCD interface state traps and BCCD bulk traps capture signal charge and then release the captured charge back into the CCD channel as described in Section 4.3. There will be fluctuations in the total number of carriers (signal charge) trapped at any instant of time. These fluctuations cause a SCCD trap noise with variance σ_{TP} [17] of:

$$\sigma_{TP} = .7\ k\ T\ N_{ss}\ A \qquad (7)$$

where: k = Boltzmann's constant (eV/°K)

T = Temperature (°K)

N_{ss} = Density of Fast States $(cm^2 - eV)^{-1}$

A = Area of Potential Well (cm^2)

The variance of the trap noise for BCCD is about 1/5 the variance described by equation (7).[19] This is due to the lesser density of bulk traps compared to interface state trap.

A typical trap noise level can be obtained by letting,

$k = 8.617*10^{-5}$ eV/°K

$T = 300$ °K

$N_{ss} = 1*10^{10}$ $(cm^2 - eV)^{-1}$

$A = 1.29*10^{-5}$ cm^2

to give σ_{TP} = 48.3 electrons.

4.4.4 Input Noise

The amount of noise introduced at the input strongly depends on the input technique. Noise results from fluctuations in the associated voltage levels, the pulse width that determines the amount of charge injected, the dynamic setting of charge, the distribution of signal charge, and capacitive pick-up from clock pulses. The lowest-noise input technique has produced noise variance $\sigma_{IN}{}^2$ approaching:[9]

$$\sigma_{IN}{}^2 = \frac{1}{q^2} \left(\frac{2}{3} K_3 \, k \, TC_i \right) \quad (8\ )$$

where: q = Electron Charge (Coulomb)

K_3 = eV → Coulomb-Volt $(1.602*10^{-19})$

k = Boltzmann's Constant (eV/°K)

T = Temperature (°K)

C_i = Input Capacitance (Farad)

The input noise RMS electrons σ_{IN} are typically 33 for the following parameters.

where: $q = 1.602*10^{-19}$ Coulomb

$K_3 = 1.602*10^{-19}$

$k = 8.617*10^{-5}$ eV/°K

$T = 300$ °K

$C_i = 1*10^{-14}$ Farad

4.4.5 Output Noise

The noise at the output depends directly upon the output technique. Although floating gate and MOSFET outputs can theoretically be expected to be the least noisy, most CCD outputs have noise measured at the level predicted for floating diffusion and RC-bandwidth limited outputs.[10] This noise level is thermal RC noise whose variance is the same as that given for the input noise variance. Typical RMS electrons are about 100 to 180, which is higher due to higher capacitance.

4.4.6 Miscellaneous Noise

Clock noise is not clock feedthrough at the fundamental clock frequency, but is essentially white noise in the signal frequency spectrum. This noise source is suspected to be due to feed-through capacitance of the clock voltage to floating diffusions. There has been little discussion in the literature of this noise and no quantitative measurements.[20]

1/f noise has been predicted to be absent in CCD's [17] and has not been observed. 1/f noise is present in MOSFET's and will contribute to the overall noise if they are used at the output of CCD's.

4.4.7 Simulation - Model

Transfer, thermal shot, trap, input, and output noise is incorporated in the simulation. The standard deviation (RMS electrons) for the noise sources are those described in the respective sections. Rather than adding the noise effects in at the output, they are incorporated where they would occur in an actual device. The transfer, thermal shot, and trap noise is added in at each transfer. The noise is Gaussian with standard deviation determined separately for each noise source.

The transfer noise standard deviation depends upon the CTI(e) which is incorporated in the simulation as described in Section 4.3.3. The number of carriers in a charge packet (Ns) changes at each transfer, therefore, the variance is changed at each transfer in the simulation.

The thermal shot noise standard deviation is a function of dark current density (J_D) whose average value is determined in the simulation and described in Section 4.5. Potential well area (A) and clock frequency are simulation inputs.

Trap noise standard deviation depends upon potential well area (A) and

temperature (T) which are simulation inputs. The density of fast states (N_{SS}) is incorporated in the simulation.

Input and output noise standard deviation requires temperature (T) as a simulation input. The input capacitance (.01 pF) and output capacitance (.1 pF) are incorporated in the simulation.

4.5 DARK CURRENT

4.5.1 Description

Since a CCD is normally operated in deep depletion there is a thermal generation of electrons which, with time, will reestablish an equilibrium condition (dark current). Thermal generation of electrons originate principally from three sources; the bulk depletion region, the neutral bulk, and the S_i-S_iO_2 interface.

The dark current density in amp/cm^2 due to generation in the bulk depletion region (J_{gd}) is given by:

$$J_{gd} = \frac{q\, n_i\, x_d}{2\, t_d} \tag{9}$$

where: q = Electron Charge (Faraday F)
n_i = Intrinsic Carrier Concentration (cm^{-3})
x_d = Depletion Width (cm)
t_d = Carrier Lifetime (sec.)

The dark current density due to generation in the neutral bulk (J_{gb}) is given by:

$$J_{gn} = \frac{q\, n_i^2\, L_n}{N_R\, t_d} \tag{10}$$

where: L_n = Carrier Diffusion Length (cm)
N_R= Density of Recombination-Regeneration Centers in the Bulk (cm^{-3})

The dark current density due to generation at the S_i-S_iO_2 interface (J_{gs}) is given by:

$$J_{gs} = \frac{q\, n_i\, a_T\, v_{th}\, N_{st}}{2} \tag{11}$$

where: a_T = Trap Capture Cross Section (cm^2)
v_{th} = Carrier (Electron) Thermal Velocity (cm/s)
N_{st} = Concentration of Recombination-Regeneration Centers at the interface (cm^{-2})

The total dark current density (J_D) is:

$$J_D = J_{gd} + J_{gn} + J_{gs} \tag{12}$$

The dark current density is temperature dependent due to the temperature dependence of the intrinsic carrier concentration (n_i). The functional relationship between n_i and temperature has been empirically determined to be:[21]

$$n_i = 1.5 * 10^{33} T^3 \exp\left(\frac{-1.21}{kT}\right) \tag{13}$$

where: T = Temperature (°K)
k = Boltzmann's Constant (eV/°K)

This expression is valid down to 250 °K.[22] Below this temperature, the carrier concentration reaches a fixed level (exhaustion region).[23]

Spatial variation in dark current generation is primarily due to spatial variation of interface recombination-regeneration centers (N_{st}). N_{st} can range between $1*10^9$ to $1*10^{11}$ cm^{-2}. Good control over device processing variables leads to a Rayleigh distribution of N_{st} skewed toward values of $1*10^9$ (cm^{-2}). This leads to a reduction in average dark current generation and to a minimization of dark current variations.

The dark current leads to a collection of electrons in a potential well according to:

$$\text{\# of Electrons} = \frac{J_D\,A}{g\,f_c}$$

where: A = Area of Potential Well (cm^2)
f_c = Clock Frequency (Hz)

Typical values for dark current calculations are:

$q = 1.64 * 10^{-24}$ F	$a_T = 1 * 10^{-15}$ cm^2
$n_i = 1.6 * 10^{10}$ cm^{-3}	$v_{th} = 8 * 10^5$ cm/s
$x_d = 1 * 10^{-4}$ cm	$N_{st} = 1 * 10^{10}$ cm^{-2}
$t_d = 1 * 10^{-4}$ s	$A = 1.29 * 10^{-5}$ cm^2
$L_n = 5.6 * 10^{-2}$ cm	$f_c = 1 * 10^4$ Hz
$N = 5 * 10^{14}$ cm^{-3}	

These values give:

$J_{gd} = 1.27\ nA/cm^2$

$J_{gn} = .046\ nA/cm^2$

$J_{gs} = 10.18\ nA/cm^2$

The total dark current density is:

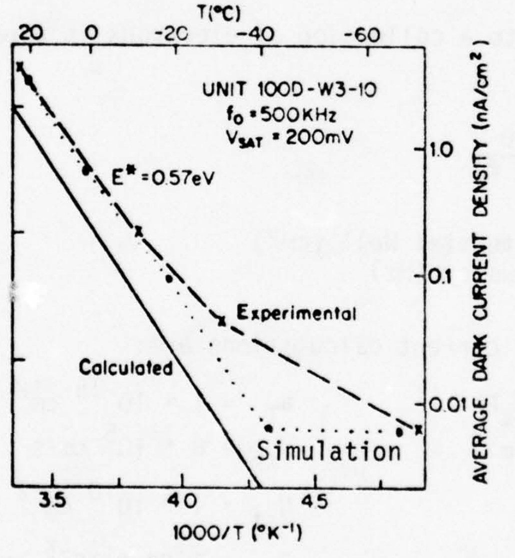
$J_D = 11.496\ nA/cm^2$

and the number of elections in the potential well is 81.8.

4.5.2 Simulation - Mcdel

The dark current calculations require as inputs; temperature, potential well area, and clock frequency. All other variables are contained in the simulation.

Figure 47 shows experimental, calculated, and simulation dark current density as a function of temperature.[24]



———————————— Calculated [24]

x----------------x Measured [24]

•................• Simulation Characteristics

FIGURE 47 . DARK CURRENT DENSITY AS A FUNCTION OF TEMPERATURE

As Figure 47 indicates the dark current density, as simulated, closely follows experimental measurements down to -20°C (250°K). At lower temperatures the simulation start to deviate as discussed in Section 4.5.1 (Equation 13). For temperatures below -40°C the dark current density in the simulation is constant.

The number of electrons that fill the potential wells due to dark current is a function of time (clock frequency). Figure 48 is the result of simulation runs showing the effects of temperature and clock frequency on dark current density (J_g) and number of electrons per well.

4.5.3 Reduction of Dark Current

Cooling can be used to drastically reduce the dark current density. Section 4.5.2 shows that cooling the CCD to -20°C from room temperature results in two orders of magnitude reduction in dark current density. CCD's as IR detectors and CCD's for signal processing from IR detectors are under development by many companies. Cooling containers developed for IR systems are commercially available [25] and could be used for cooling CCD signal processing sub-systems to desired temperatures.

Dark current density can also be reduced by adequately controlling the fabrication process. In particular, the largest contributor to the total dark current density is the interface dark current density. This source can be reduced by reducing the number of recombination-regeneration centers at the interface. This is accomplished by choosing the optimum type of silicon and the type of oxidation, and using the proper annealing procedures.

Another method of reducing the effects of dark current is to subtract the accumulated background charge from the charge packets. This technique should be made adaptable to changes that increase in temperature and clock period and be sensitive to differences in dark current densities from device to device.

4.5.4 Radiation Effects

The most serious limitation on CCD performance is the increased dark current density levels which are observed in the neutron environment. Indications are that BCCD's are superior to SCCD's in an ionizing radiation environment. Transfer efficiency is also worse for SCCD's at lower radiation levels.[26]

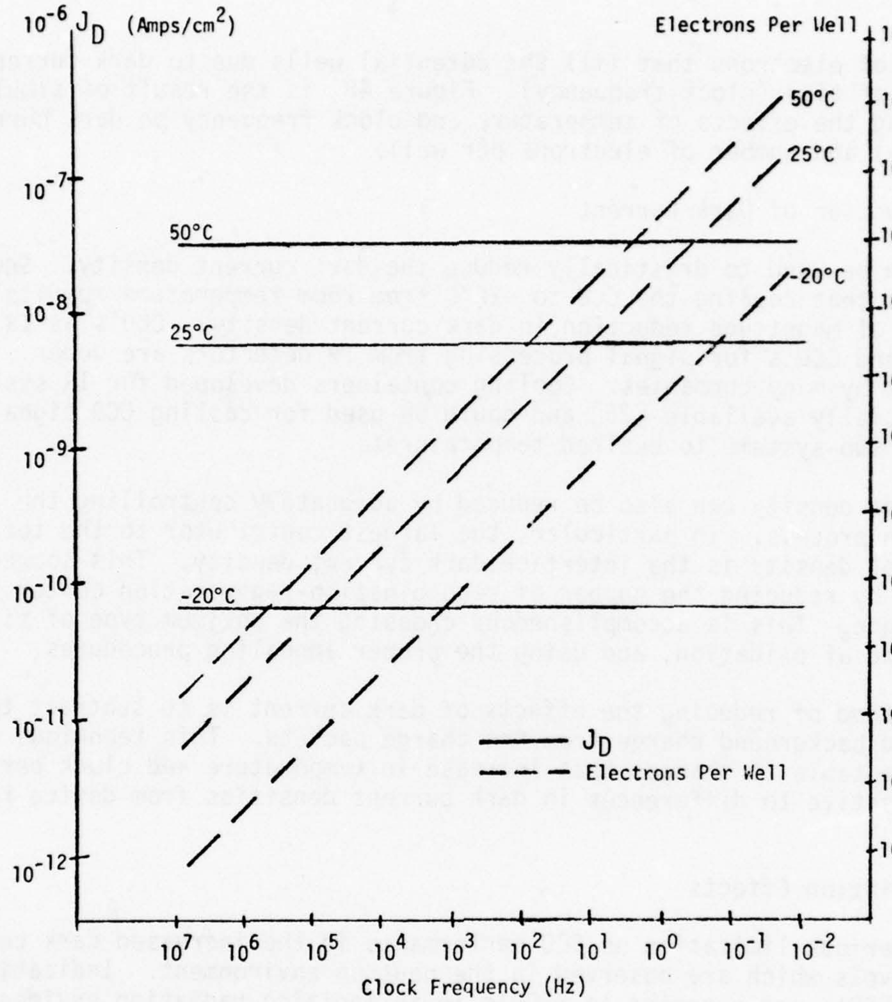


FIGURE 48 . DARK CURRENT DENSITY AND ELECTRONS PER WELL VERSUS TEMPERATURE AND CLOCK FREQUENCY

4.6 CCD INPUT SAMPLING

The input sampling technique used in CCD's is critical to their performance. An important problem is attaining a charge packet in the CCD which is a linear function of the input signal amplitude. In addition, the sampling process in CCD's will have the same general specifications applicable to analog-to-digital converters.

4.6.1 *Input Structure and Linearity*

Figure 49 shows a typical CCD input structure. It is characterized by a diffusion source of electrons and perhaps two input sampling gates which transfer the desired charge to the potential well formed by clock voltage ϕ_1. If a signal is applied directly to the source and is strobed into the CCD by pulsing the gates, the result is inherently non-linear. Although there are other variations, the technique which has provided the best linearity, of up to 50 percent of the full potential well, is called the "fill and spill" method.[8-20] In this technique, the signal is applied to the first gate G_1, and a DC level or the signal is placed on the second gate G_2. A sampling pulse applied to the source will inject an excess of charge into the device. As the clock voltage and pulse is removed, the excess charge is extracted from the CCD, limited by the signal gate potential.

A method has been suggested [27] which uses a feedback approach to achieve a linear input to a CCD. In this method, a tap is placed after the input gates which senses the magnitude of the sampled charge. The tap output is fed back to a differential amplifier which subtracts the tap value from the input. The resultant is fed to the signal gate of the CCD. During a sample interval, the sampled charge is thus forced to be proportional to the input sample value. Although this method greatly increases the linear range of the full potential well, its bandwidth capability for wideband applications is limited.

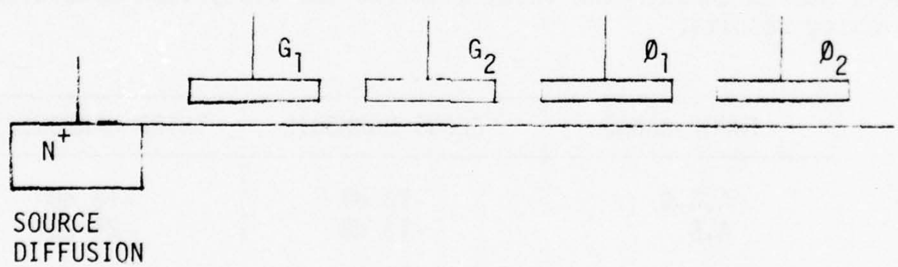


FIGURE 49.

4.6.2 Sampling Aperture

As discussed generally in Section 3, the input sampling aperture will affect the bandwidth performance of the CCD. This is analogous to the sampling aperture-resolution requirements of A/D converters. The accuracy

of the sampling process will be determined to a large extent by the width of the sampling aperture. In specifying sampling aperture in an A/D converter, a conventional approach is to limit the signal excursion to less than one-half the least significant bit during the sampling aperture. This specification sets the aperture size limit, δ, to approximately $(T_p/2^{N-1})$ where T_p is the period of the highest frequency to be sampled and N is the number of quantization bits.

If we consider only the bandwidth capabilities of the sampling aperture, the 3 dB bandwidth can be determined by the frequency response:

$$S_f = \frac{\sin \frac{2\pi\delta}{T_p}}{\frac{2\pi\delta}{T_p}} = .707$$

This yields $\delta/T_p = .22$. It is thus apparent that the bandwidth criterion is much less restrictive of the sampling aperture than the conventional sampling noise criterion for A/D converters. The key issue is the magnitude of the uncertainty in the sample amplitude created by the sampling aperture. If the aperture acts as a pure signal average, no noise is introduced. However, if the charge injection varies depending upon, for example, whether the slope of the signal is positive or negative, then a sampling error signal will occur. This error signal will act as a noise added to the signal and if high enough could degrade the signal-to-noise ratio of the processor. No sampling error signal was derived during the study and none was included in the CCD simulation.

4.6.3 CCD Input Model

The CCD input model used for the simulation included the effect of non-linearities and sampling aperture. A piecewise linear approximation to the input, based upon measured values, is shown in Figure 50 . Harmonic analysis of signals passed through the input with the two distortion conditions gave the following results.

INPUT RANGE	SECOND HARMONIC	THIRD HARMONIC
A,B,C	-13 dB	-18 dB
A,B	-13 dB	-24 dB

These distortion levels were too high to consider anything other than the linear operating range, A. With the linear region covering only 4/28 = 14% of the full well, the total dynamic range is limited. For the simulations, a 2.0 percent background bias charge was used, further reducing the signal range.

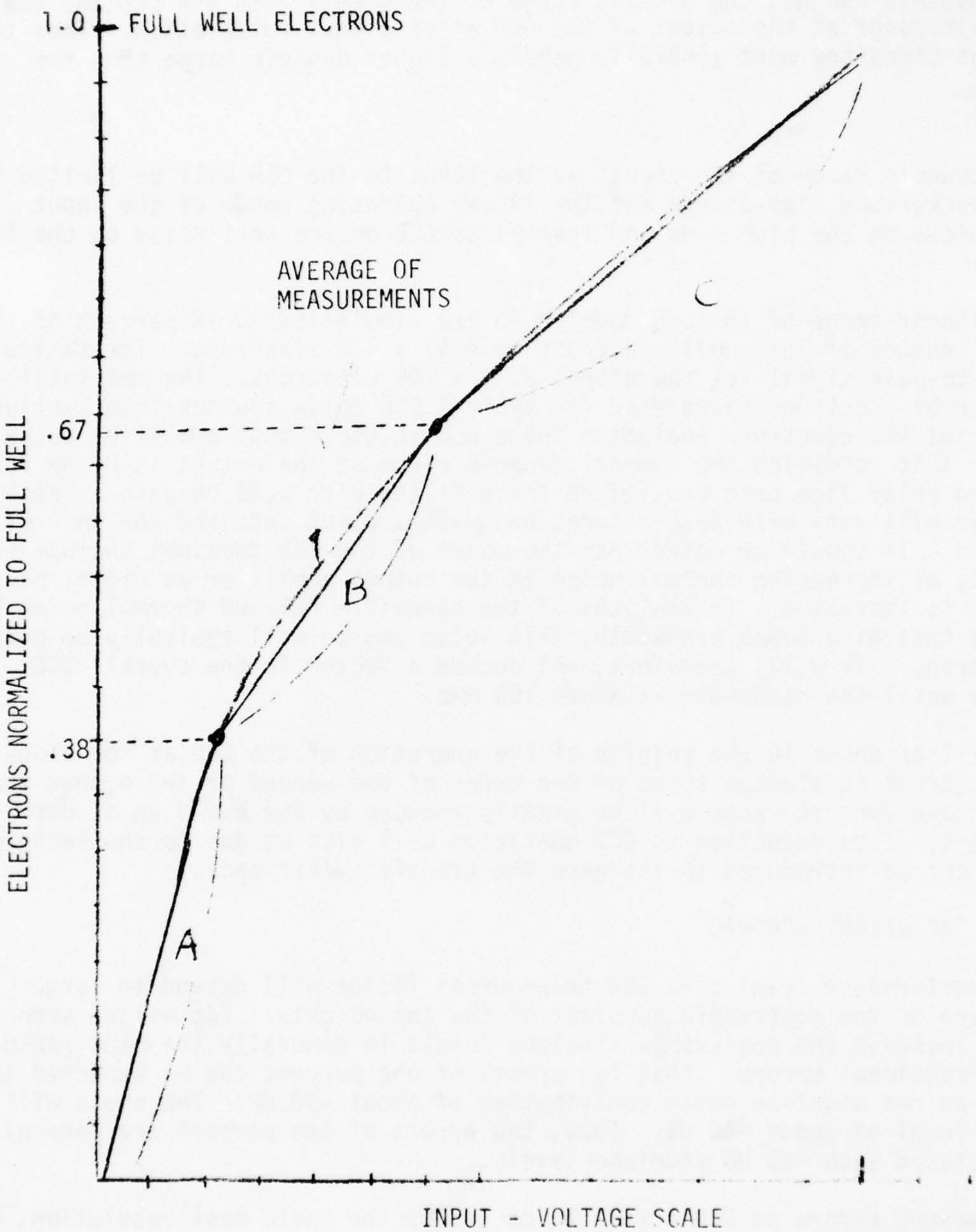


FIGURE 50. MEASURED INPUT TRANSFER CHARACTERISTICS

4.7 DYNAMIC RANGE

The dynamic range of a device can be defined as the ratio of the peak to peak signal before saturation to noise. In a CCD processor one can define two dynamic ranges, the dynamic range of the signal into the CCD and the dynamic range at the output of the CCD after signal integration. Thus the output circuitry must generally handle a higher dynamic range than the input.

The dynamic range of the signal at the input to the CCD will be limited by the background bias charge and the linear operating range of the input technique on the high side and thermal or CCD device self noise on the low side.

The linear range of the CCD modeled in the simulation is 14 percent of the total number of full-well electrons or 4.57×10^6 electrons. The maximum peak-to-peak signal is, therefore, 2.28×10^6 electrons. The rms total number of electrons identified for typical CCD noise sources from Section 4.4 is about 160 electrons including those due to the output amplifier noise. Under this condition the nominal dynamic range at the output is 83 dB for a tapped delay line case and 103 dB for a filter with a 20 dB gain. These values will vary with temperature, bandwidth, clock rate and the gain of the filter. It should be noted that the model of the CCD does not include the effect of increasing thermal noise in the output amplifier as signal bandwidth is increased. An analysis of the bandwidth related thermal noise [8-17] shows that at a 5 MHz bandwidth, this noise source will typically be only 6 electrons. It will, therefore, not become a factor in the overall CCD noise until the bandwidth is above 100 MHz.

It will be shown in the results of the operation of the CCD at low clock rates,creating storage times of the order of one second or above,that the effective dynamic range will be greatly reduced by the build up of dark current. Some reduction in CCD operation will also be due to the background bias charge introduced to increase the transfer efficiency.

4.8 TAP WEIGHT ACCURACY

The performance level of a CCD transversal filter will depend in large measure on the achievable accuracy of the tap weights. Tap weight errors will increase the achievable sidelobe levels in generally the same ratio of the fractional errors. That is, errors of one percent can be expected to have an rms sidelobe noise contribution of about -50 dB. The peaks will be at a level of about -40 dB. Thus, tap errors of one percent are generally associated with -40 dB sidelobe levels.

Tap weight errors in CCD's will be caused by the basic mask resolution, mask misalignment, charge transfer efficiency and non-uniform charge distribution. Non-uniform charge distribution is due to the non-ideal nature of a split-gate tap. That is, the computation of gate dimension assumes a square gate size, but edge effects on the gates effectively rounds the edges creating a slight error in gate capacitance. The latter three causes are not generally considered to be of major importance. However, measurements of tap weight

errors on a split-gate transversal filter at RCA showed tap weight errors which ranged up to a maximum of 6 percent with a standard deviation of 1.75 percent. The simulation has included consideration of tap weight errors from .1 to 10 percent.

4.9 SIGNAL ISOLATION

4.9.1 Potential Well Isolation

It is important that the charge stored in a potential well is influenced only by its own and neighboring control gates to prevent crosstalk and undesirable losses. This is assured by surrounding the CCD channel with a potential barrier preventing the leaking of charge from the well in the transverse direction as shown in Figure 51. This barrier also prevents clock busses from interferring with the signals in the wells. Well to well isolation along the CCD channel is controlled by the gate clock signals.

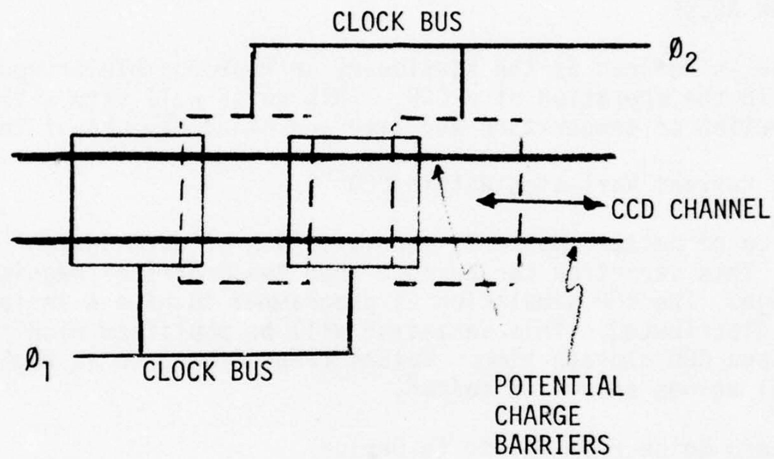


FIGURE 51. CCD CHANNEL ISOLATION

4.9.2 Input-Output Feedthrough

CCD delay lines often exhibit direct coupling from the input signal to the output. This can be due to two causes. If the clock signals and input sampling pulse are not timed properly, it may allow the input charge to propagate directly through the CCD. This is an unusual condition and will only be observed with a control/clock timing drift or failure. Parasitic capacitance on the CCD package, wire bonds or external circuitry can provide a direct coupling from the input to the output. This problem can be aggravated by the use of dual-in-line packages which have parallel closely spaced leads.

4.9.3 Clock Feedthrough

The CCD output structure whether a signal is developed from the drain or a floating gate is such that clock feedthrough is inherent in the process. No

output technique has been reported which eliminates feedthrough. The clock signal must, therefore, be cancelled or filtered. These processes may be aided by the incorporation of clock drivers and controls on the CCD chip.

The problem of clock filtering is relatively straightforward in applications where the sample rate is much greater than the signal bandwidth. However, in applications such as binary coded correlators the clock signal may be identical to the code rate. In these cases, the clock can only be removed by cancellation. Experiments have been performed [28] using sine wave clocks for operation of CCD's at frequencies as high as 100 MHz. The sine wave clocks may not provide maximum transfer efficiency but since they contain no significant spectral components beyond the fundamental they are relatively easy to cancel. On-chip cancellation can also improve performance since the on-off chip driving creates slight mismatches in the clock signals which lead to high clock spikes. A sample-and-hold operation after clock cancellation can be used to remove the spikes.

4.10 PATTERN NOISE

Pattern noise is defined as the stationary or reproducible irregularities encountered in the operation of a CCD. This noise will vary within a given CCD as a function of temperature and time and among devices of the same type.

4.10.1 Dark Current Variation Within CCD

A large source of pattern noise is the variation of dark current among the CCD stages. This variation can be more than two orders of magnitude from stage to stage. The CCD simulation is programmed to give a variation which is Rayleigh distributed. This variation will be amplified with increasing temperature and CCD storage time. Values range from 2 to as high as 100 na/cm^2 which typical values around 10 na/cm^2.

4.10.2 Pattern Noise From Device to Device

Variations in characteristics from device to device can adversely affect the performance of a system where multiple CCD's are used or when devices are replaced due to failures. CCD parameters which can be expected to vary from device to device include the input structure linearity, tap weight errors, charge transfer efficiency and temperature coefficients.

4.11 CCD CHARACTERISTICS - SUMMARY

Tables 28 and 30 list a summary of key CCD developments reported in the literature. A short summary of extremes is listed in Table 28, and a more complete listing is given in Table 30. The CCD simulation program results have been correlated with these general results to assure conformity. Table 29 summarizes the noise sources with their mean, variance and distribution as incorporated in the CCD simulation.

TABLE 28. SUMMARY OF REPORTED CCD CHARACTERISTICS

° Maximum Number of Stages	910
° Minimum Transfer Inefficiency	$1 * 10^{-5}$
° Maximum Sample Rate	180 MHz
° Minimum Dark Current Density	$1.5 \frac{nA}{CM^2}$ @ 25°C
° Maximum Dynamic Range	75 dB
° Minimum Harmonic Distortion	-45 dB

TABLE 29. CCD NOISE SOURCES IN SIMULATION

Noise Source	Mean	Variance	Distribution
Input/Output	0	$2K_3 \; K \; TC_i/g^2$	Gaussian
Shot	0	$J_D \; A \; K_2/g \; f_c$	Gaussian
Trap	0	$.7K \; T \; N_{SS} \; A$	Gaussian
Filter Tap Weights	Weight Value	$(\text{Percent Error})^2$	Gaussian
Transfer	0	$2 \; e \; N_S$	Gaussian
Dark Current*	$J=J_{gd}+J_{gn}+J_{gs}$	$J^2/(\pi/2)$	Rayleigh (J_{gs} Term Only)

* See Section 4.5 for Expanded Equation.

TABLE 30. SUMMARY OF REPORTED CCD CHARACTERISTICS

TYPE	STAGES	CLOCK PHASE	SAMPLE RATE	TRANSFER INEFFICIENCY	DARK CURRENT	MASK ACCURACY	DYNAMIC RANGE	S/N	HARMONIC DISTORTION	APPLICATION	REFERENCE
SCCD	500	4	200 kHz	$3*10^{-4}$	2 NA/CM^2	.05 MILS	75 dB		-45 dB	BANDPASS FILTER	R. W. Broderson, et al, "500-STAGE CCD TRANSVERSAL FILTER FOR SPECTRUM ANALYSIS" IEEE VOL. ED-23 FEB. '76
SCCD	500	4	500 Hz-100 kHz	$1*10^{-4}$	2 NA/CM^2	.05 MILS	75 dB		-45 dB	CHIRP FILTER	
SCCD	63	2	80 kHz			.05 MILS		62 dB	-40 dB	LOWPASS FILTER	R. D. Baertsch, et al, "DESIGN & OPERATION OF PRACTICAL CHARGE TRANSFER TRANSVERSAL FILTERS", IEEE VOL. ED-23,2/76
SCCD	256	3	8 MHz	$5*10^{-5}$	10 NA/CM^2			60 dB	-40 dB	ANALOG DELAY	D. A. Sealer, et al, "ANALOG & CHARACTERIZATION OF CCD's FOR ANALOG SIGNAL PROCESSING", IEEE '75 COMMUNICATION CONF.
SCCD	13	3	10 kHz-5 MHz	$1*10^{-3}$						MATCHED FILTER	D. R. Collins, et al, "ANALOG MATCHED FILTERS USING CCD's NEREM '72
SCCD	21	3	60 kHz	$5*10^{-3}$						CHIRP FILTER	
SCCD	250	2	250 kHz-8 MHz					62 dB	-40 dB	ANALOG DELAY	M. F. Tompsett, et al, "USE OF CCD's FOR DELAYING ANALOG SIGNALS", IEEE VOL. SC-8, APR '73
SCCD	500	3	1 MHz							ANALOG DELAY	
SCCD	100	3	3 kHz-3 MHz	$3*10^{-4}$ $9*10^{-4}$	10-100 NA/CM^2					ANALOG DELAY	D. J. Burt "PERFORMANCE LIMITATIONS OF CCD's" INTER. CONF. ON TECHNOLOGY & APPLICATIONS OF CCD's" SEPT. '74
SCCD	40	2	1-2 MHz	$5*10^{-4}$						ANALOG DELAY	
BCCD	40	2	20 MHz	$1*10^{-4}$						ANALOG DELAY	
BCCD	100x100	2	500 kHz		2 NA/CM^2 25°C .6 NA/CM^2 - 6°C .1 NA/CM^2 -20°C .01 NA/CM^2 -60°C		52 dB			IMAGER	R. H. Dyck, et al, "LOW LIGHT LEVEL PERFORMANCE OF A CHARGE-COUPLED AREA IMAGING DEVICE", INTER. CONF. ON TECH. & APPLICATIONS OF CCD's", SEPT. '74
PCCD	128	4	100 kHz-135 MHz	$5*10^{-5}$						ANALOG DELAY	M. J. Theunissen, et al "PCCD TECHNOLOGY AND PERFORMANCE" INTER. CONF. ON TECHNOLOGY & APPLICATION OF CCD's", SEPT. '74
SCCD	24	3	8 kHz-20 kHz					70 dB	.02-.3%	ANALOG DELAY	D. A. Sealer, et. al., "A DUAL DIFFERENTIAL CHARGED-COUPLED ANALOG DELAY DEVICE", IEEE, Vol. ED-23, Feb '76
SCCD	48	3	8 kHz-20 kHz					70 dB		ANALOG DELAY	
BCCD	150	4	25 kHz-1 MHz	$2*10^{-5}$	3-8 NA/CM^2					ANALOG DELAY	R. W. Brodersen, et. al., "A 500-STAGE CCD TRANSVERSAL FILTER FOR SPECTRAL ANALYSIS", IEEE , Vol. ED-23, Feb. '46

TABLE 30. SUMMARY OF REPORTED CCD CHARACTERISTICS (CONTINUED)

TYPE	STAGES	CLOCK PHASE	SAMPLE RATE	TRANSFER INEFFICIENCY	DARK CURRENT	MASK ACCURACY	DYNAMIC RANGE	S/N	HARMONIC DISTORTION	APPLICATION	REFERENCE
SCCD	800	3	100 KHz- 1 MHz	2.4×10^{-4}						BANDPASS FILTER	C. R. Henes, "A Self Contained 800 Stage CCD Transversal Filter", CCD Conference '75, San Diego
BCCD	150	4	500 KHz	$1 * 10^{-5}$	3-8 NA/CM^2					ANALOG DELAY	R. N. Brodersen & S. P. Emmons, "The Measurement of Noise in BCCD", CCD Conference '75, San Diego
PCCD	130	4	10 KHz- 105 MHz	$1 * 10^{-3}$ @27°C $5.5 * 10^{-4}$ @-196°C $1 * 10^{-3}$ @-243°C $1 * 10^{-2}$ @-255°C $2 * 10^{-2}$ @-268°C						ANALOG DELAY	A. J. Steckl, "Low Temperature Silicon CCD Operation", CCD Conference '75, San Diego
SCCD	100	4	10 KHz	$7.5 * 10^{-4}$ @27°C $4 * 10^{-4}$ @-196°C $1.4 * 10^{-3}$ @-268°C						IR SIGNAL PROC.	
BCCD	128	2	1 MHz- 50 MHz	$1.88 * 10^{-4}$ $-9.34 * 10^{-4}$						ANALOG DELAY	L. J. Nicastro, Internal RCA Report
SCCD	64	3		$2 * 10^{-4}$ $-1.2 * 10^{-3}$	1.5 NA/CM^2* -5 NA/CM^2		*TRANSFER GATES IN ACCUMULATION			ANALOG DELAY	G. J. Declerck, et al, "Low Dark Current CCD", CCD Conference '76, Edinburgh
PCCD	128	4	180 MHz	$2 * 10^{-5}$						ANALOG DELAY	L. J. Esser in "Solid State Imaging", Jespers, De Wiele, & White, Noordhoff, 1976

GLOSSARY OF CCD TERMS

a_T	trap capture cross section
A	active area of potential well (mil^2)
A°	angstrom (10^{-10} meter)
BCCD	buried channel CCD
C	gate capacitance
C_i	CCD input capacitance
C_{ox}	MOS gate oxide capacitance per unit area
CCD	charge coupled device
CTE	charge transfer efficiency
CTI	charge transfer inefficiency
d_{ch}	effective thickness of channel implant
d_{ox}	oxide thickness
ΔV	two phase clock voltage bias
e	charge transfer inefficiency CTI
eV	electron volt
ε_{ox}	permitivity of silicon dioxide
ε_{si}	permitivity of silicon
f_c	clock frequency
F	Faraday
J_D	dark current density (amperes/cm^2)
J_{gd}	dark current density from bulk depletion
J_{gn}	dark current density from neutral bulk
J_{gs}	dark current density from S_i-S_iO_2 interface
k	Boltzmans constant (8.617×10^{-5} eV/°K)
K_1	electrons per coulomb (6.28×10^{18})
K_2	Faraday's per coulomb (1.036×10^{-5})
K_3	coulombs per electron (1.602×10^{-19})
L_n	carrier diffusion length
MOS	metal oxide semiconductor
μ	micron
n_i	intrinsic carrier concentration
nm	nanometer
N_R	density of recombination - regeneration centers
N_S	number of carriers in a charge packet

N_{SS}	density of fast states
N_{st}	concentration of recombination - regeneration centers at the interface
pf	picofarad
q	electron charge (1.602×10^{-19} coulomb, 1.64×10^{-24} F)
Q_S	charge stored in CCD potential well (electrons)
S_i-S_iO_2	silicon-silicon dioxide
SCCD	surface channel CCD
σ_{IN}	rms input noise
σ_{SN}	rms shot noise
σ_{TP}	rms trap noise
σ_{TR}	rms transfer noise
t_d	carrier lifetime
T	temperature (°K)
v_{th}	carrier thermal velocity
V	volts
V_P	pulse potential applied to CCD gate with respect to adjacent gate
x_d	carrier lifetime

5. SIMULATION DEVELOPMENT

5.1 SIMULATION SOFTWARE ORGANIZATION

The simulation software was written in modular form with over 21 subroutines for each device simulation. The reason for a large number of subroutines is that the program was designed to be run on a mini-computer with at most 28K of memory. This modularity allows for extensive overlaying as well as ease of debugging and changing of the program. Figure 52 is the block diagram of the overlay structure (i.e., the subroutines residing in an overlay) for the delay line and tapped delay line. The main program is responsible for calling in the overlays and maintaining the integrity of common areas. Table 31 is a brief description of each subroutine referenced in Figure 52 .

Figure 53 is a block diagram of a linear FM matched filter which was simulated. Figure 54 is the corresponding block diagram of the overlay structure for Figure 53 . Table 32 is the brief descriptions of each subroutine referenced in Figure 54.

The random variables used by the program were generated offline onto a mass storage device (magnetic tape). Only standard normal random variates were generated using the direct approach [29]. The random variates used by the program were read from the device and transformed to the appropriate distributions.

Table 33 is a listing of the program questions to the user for the delay line and Table 34 is the corresponding prompting for the linear FM matched filter. Appendix A and B are the listings of the programs for each device.

The devices that can be simulated by the two programs are a delay line, a tapped delay line, and a matched filter. The delay line represents a transformation of the form:

$$g(nT) = af(nT-NT)$$

where NT is the delay (time spent in the device), T the sampling rate and a the perturbation due to the device (a=1 correspondence to a lossless device). The tapped delay line (the number of stages is equal to number of taps) represents the samples of a signal being weighted and summed,

$$g(nT) = \sum_{i=1}^{N} a_i \, f(nT-iT)$$

where a_i's are the weights, iT the i^{th} sample of the signal and g(nT) the n^{th} output of a summer. The matched filter (convolver) is made up of four tapped delay lines whose weights have been chosen to be samples of the expected receive signal (weights are correlated/matched in some manner with the expected signal samples). Examples of weights are $\pm$ 1 for derivative phase and binary phase waveforms,and linear FM weights (samples of sin/cos).

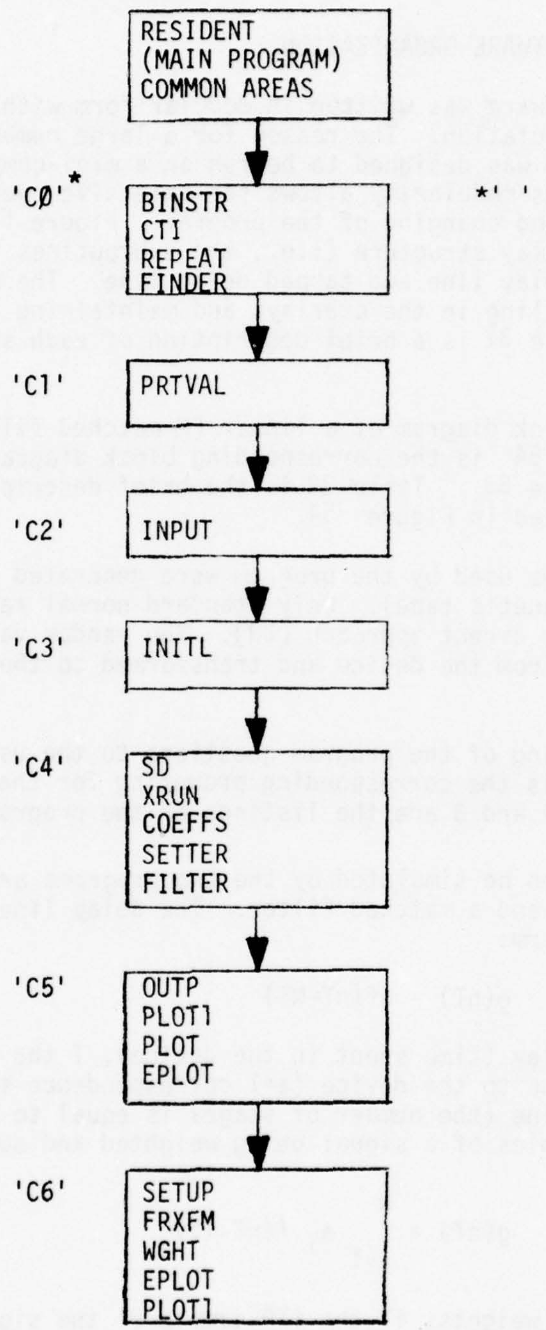
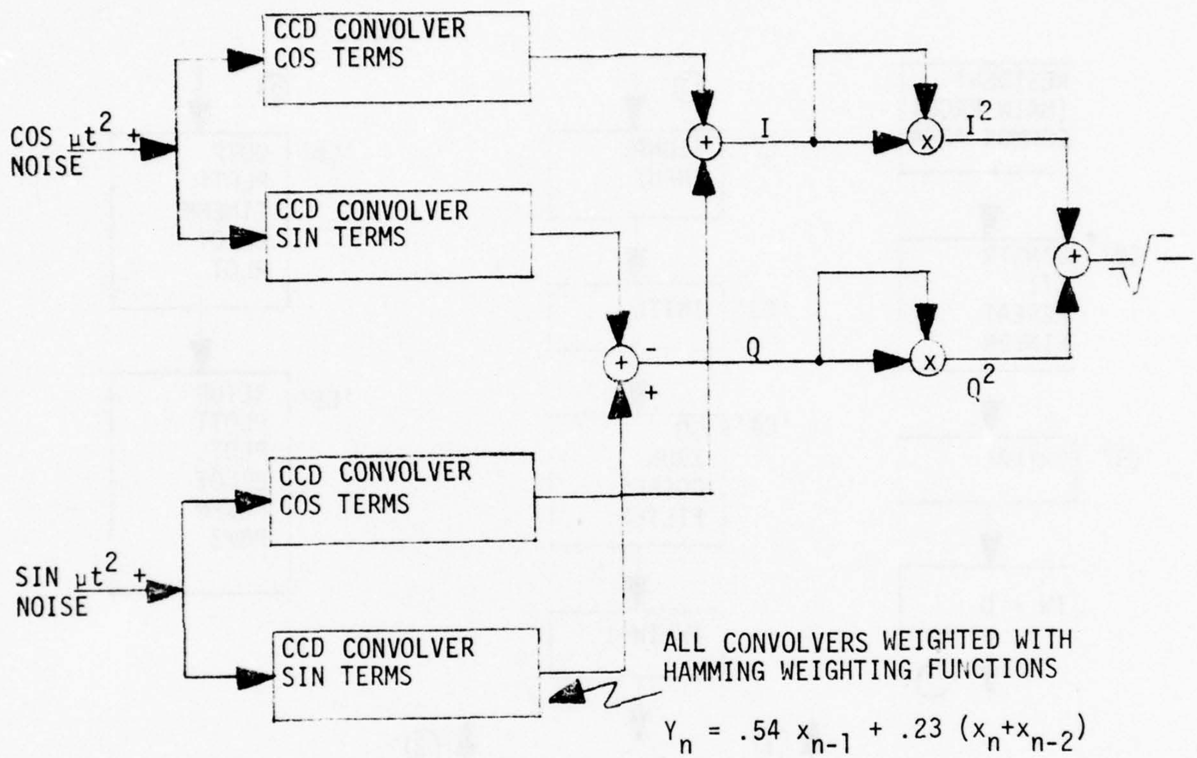


FIGURE 52. BLOCK DIAGRAM OF OVERLAY STRUCTURE FOR SIMULATION MODEL OF DELAY LINE AND TAPPED DELAY LINE



$\mu = \frac{BW}{2T_P}$

BW = BANDWIDTH OF THE SIGNAL

T_P = LENGTH OF THE SIGNAL

FIGURE 53. BLOCK DIAGRAM OF LINEAR FM MATCHED FILTER

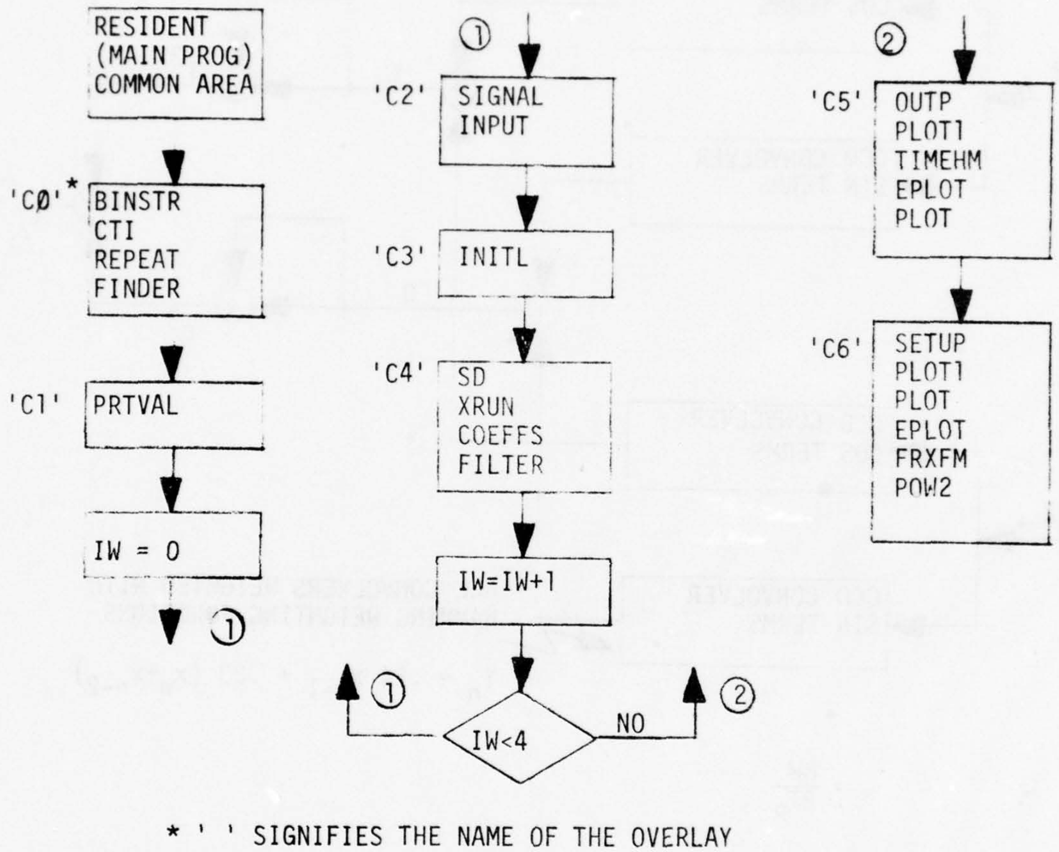


FIGURE 54. BLOCK DIAGRAM OF OVERLAY STRUCTURE FOR SIMULATION MODEL OF LINEAR FM MATCHED FILTER

TABLE 31. A BRIEF DESCRIPTION OF THE SUBROUTINES REFERENCED IN FIGURE 52

BINSTR - Is responsible for interrogating the user as to the structure of the CCD (area, length, temperature, etc.), the input waveform (duration, amplitude, pulse/sinusoids, etc.), and the outputs desired for each run. Table 33 gives the questions asked by the subroutine.

COEFFS - Either computes the tap weights for a CW signal or reads in the tap weights from .DAT slot +4 for an arbitrary transversal filter. Appendix C gives the listing of a design program developed in [30].

CTI - Computes the Charge Transfer Inefficiency (CTI) for either buried or surface devices. The CTI is a function of background charge.

EPLOT - Is a general plot routine which plots an array of values on a scale of 0 to 100 dB normalized to the maximum value of the array.

FILTER - Computes the filter response by summing the weighted outputs of each cell on the second clock pulse.

FINDER - Performs bookkeeping needed for multiple runs. That is, the program has the ability to alter two of six variables.

FRXFM - Performs a decimation in frequency FFT.

INITL - Initializes the CCD before the device sees the input signal.

INPUT - Forms the input waveform. The user has the option of no signal, pulse of given length and amplitude, sinusoidal of given length and amplitude. The subroutine changes the formed input from voltage to electrons with either a linear transformation or a non-linear transform.

OUTP - Converts the output of the device from electrons to voltage storing the results on .DAT Slot +2. The subroutine is also responsible for the addition of the output noise.

PLOT - Is a general plot routine which plots out linearly a given array of data on a 132 column line printer. It is used in the program to plot the input and output responses versus time.

PLOT1 - Is a bookkeeping routine which calculates the sampled mean, variance, minimum and maximum for a specified array of data.

PRTVAL - Calculates the means and standard deviations for the CCD noise sources.

REPEAT - Performs bookkeeping for multiple runs. See subroutine FINDER.

SD - Calculates the cumulative means and standard deviations for the normal noise sources.

SETUP - Is responsible for putting the data in proper form so that different outputs maybe obtained (i.e., FFT, weighting, etc.).

TABLE 31. CONTINUED

WGHT - Performs either Hamming or Hanning weighting on a specified array of data. The weighting is in the time domain to allow suppression of the sidelobes in the frequency domain.

XRUN - Performs the bookkeeping of transferring the electrons from well to well and stage to stage. The bookkeeping includes the addition of the different noise sources and dark current.

TABLE 32. A BRIEF DESCRIPTION OF THE SUBROUTINE REFERENCED IN FIGURE 54

BINSTR - Is responsible for interrogating the user as to the structure of the CCD (area, length, temperature, etc.), the input waveform (bandwidth, duration phase, amplitude, etc.), and the outputs desired for each run. Table 34 gives the questions asked by the subroutine.

COEFFS - Computes the tap weights to match a linear FM signal.

CTI - Computes the Charge Transfer Inefficiency (CTI) for either surface or buried devices. The CTI is a function of background charge.

EPLOT - Is a general plot routine which plots out an array of values on a scale of 0 to 100 dB normalized to the maximum value of the array.

FILTER - Computes the filter response by summing the weighted outputs of each cell on the second clock pulse.

FINDER - Performs bookkeeping needed for multiple runs. That is, the program has the ability to alter two of six variables of the CCD.

FRXFM - Performs a decimation in frequency FFT.

INITL - Initializes the CCD before the device sees the input signal.

INPUT - Forms the input waveform. The user has the options of signal-to-noise, bandwidth, pulse length, phase of the return, noise only and target only. The subroutine changes the formed input to electrons from voltage with either a linear or non-linear transformation.

OUTP - Converts the output to voltage from electrons. The subroutine also combines the four separate signals from the four match filters, squares the Inphase and Quadrature channels.

PLOT - Is a general plot routine which prints out linearly a given array of data on a 132 column line printer. It is used in the program to plot the input and output responses versus time.

PLOT1 - Is a bookkeeping routine which calculates the samples mean and variance, and also finds the minimum and maximum values for a specified array of data.

POW2 - Computes the power of 2 which is greater than or equal to a specified number. Is a utility program for the FFT program.

PRTVAL - Calculates the means and standard deviations for the CCD noise sources.

REPEAT - Performs bookkeeping for multiple runs. See subroutine FINDER.

SD - Calculates the cumulative mean and standard deviations for the normal noise sources.

TABLE 32. CONTINUED

SETUP - Is responsible for putting the data in proper form so that different outputs may be obtained (i.e., FFT, weighting, etc.).

TIMEHM - Performs Hamming weighting on a specified array of data. The weighting is done on the frequency domain to suppress the time response sidelobes.

XRUN - Performs the bookkeeping of transferring the electrons from well to well and stage to stage. The bookkeeping includes the addition of the different noise sources and dark current.

TABLE 33. QUESTIONS ASKED BY THE DELAY LINE AND TAPPED DELAY LINE SIMULATION

CREATE NEW FILE ON DAT SLOT +2 Y = 0 N = 1

If user wants the output saved for later use, response should be a 0. If not, then 1. The data will be stored on file TEMPØ2.DAT for a response of 1.

NAME OF FILE XXXXXX.DAT

If response to above was a 0, then user must give the name of the file. Only restrictions are that the file name cannot begin with a numeric and all spaces must be filled in with a character or a blank.

THE NUMBER OF STAGES IN THE CCD (F10.0)

User specifies the number of stages from 1 to 600. The upper limit is only restricted by core size.

SD OF THE INITIAL STATE (F10.0)
IF < Ø, THEN NO BACKGROUND VOLTAGE ADDED

The user specifies the number of electrons for the standard deviation of the initial state of the CCD. If a negative number is given, the system will not add in background charge to the input signal.

SURFACE OR BURIED DEVICE (0 OR 1)

The user specifies a 0 for surface device and a 1 for buried device.

AREA OF THE WELL IN MIL**2

The user specifies the area of each gate.

% OF BACKGROUND CHARGE
< Ø, THEN SPECIFY TRANSFER LOST

The user specifies the % of background charge which determines the charge transfer inefficiency. If the number specified is < Ø, then the next question will ask for the lost.

FRACTION LOST EACH TIME .XXXX

If the response to the above question was negative, then user specifies the fraction lost on each transfer.

CLOCK SAVING VOLTAGE

Self explanatory.

TABLE 33. CONTINUED

PLOT OF INPUT AND OUTPUT Y=0 N=1

If user wants a plot of input and output signals, response is a zero. If not, then a 1.

FFT OF OUTPUT Y=1 N=0

If user specifies a 1, then an FFT of the output signal is plotted. If he specifies a 0, then no FFT is performed.

CLOCK FREQUENCY (F10)

User responds with the sampling frequency of the device.

THE LENGTH OF TIME OF THE RUN < 1201

The number of samples from the input signal that are processed by the CCD.

PRINT OUT INTERMEDIATE VALUES NO = 0 YES = 1

For debugging purposes, the user has the option of examining the contents of the wells.

FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N = 0 Y = 1

A DC component corresponding to feedthrough voltage is added if response is a 1. If a 0, none is added.

DURATION OF THE SIGNAL MIN = 0 MAX = 1200

The number of samples of the input which will contain a signal versus noise only.

TYPE OF SIGNAL PULSE = 0 SIN = 1

User has option of two types of signals: a pulse (response 0) or sinusoidals (response 1).

** If response to above is 0, then next question is:

INPUT LEVEL OF SIGNAL MAX = VALUE VOLTS

User specifies the amplitude of the pulse in volts.

** If response to above is 1, then the next question is:

OF SINUSOIDALS F10 < 5

User can specify up to 5 sinusoidals input.

TABLE 33. CONTINUED

FREQUENCY OF THE i SIGNAL (HERTZ)

User specifies in hertz the frequency of the i^{th} sinusoidal.

AMPLITUDE (% OF WELL) OF THE i SIGNAL

User specifies in terms of % of full well the amplitude of the i^{th} sinusoidal.

DC BIAS (% OF WELL) TERM ADDED TO INPUT #10

User responds with a DC bias added to input signal in terms of % of a full well.

NON-LINEAR INPUT WARPING Y=0 N=1

User has option of using a linear input structure (1) or a non-linear input response to the CCD.

FILTER RESPONSE COMPUTED N=0 Y=1

User has option of obtaining the output of a delay line (0) or the output from a tapped delay line (1). (Coefficients read in from DAT Slot +4 in E15.8 format.)

DARK CURRENT ADDED Y=0 N=1

Dark current added Yes = 0 No = 1.

** If response to above is 0, then next 4 questions below are asked. If a 1, then next 4 questions are omitted.

AMBIENT TEMPERATURE IN DEGREES °C

Self explanatory.

DO YOU WANT TO HOLD THE SIGNAL FOR ANY TIME Y=0 N=1

User has option of obtaining the response when the signal has been put in storage mode.

** If response to above question is 0, then the next 2 questions are asked. If not, then they are shipped.

TIME (SEC) LEFT IN DELAY LINE

Number of seconds left in delay line.

FREQUENCY CLOCK SIGNAL OUT

Output clock frequency after the storage time has been completed.

TABLE 33. CONTINUED

MULTIPLE RUN Y=# OF CHANGES N=0

User has option of changing a parameter between runs. If response is > 0, then number of runs with this variable changed. If 0, then none.

** If response to above is = Ø, then the next 5 questions are omitted.

WHICH INPUT IS TO BE CHANGED
1 = NUMBER OF STAGES, 2 = SURFACE/BURIED
3 = AREA OF WELL, 4 = STORAGE TIME (SEC)
5 = CLOCK FREQUENCY, 6 = AMBIENT TEMPERATURE

Response is the variable to be changed.

INPUT THE i VALUE

Response is to input the value for the i^{th} run.

SECOND VARIABLE CHANGING Y = NUMBER N = 0

Response is the number of times the second variable is to be changed. If 0, then none.

** If response to above 0, then skip next 2 questions.

WHICH INPUT

The variable number to be changed.

INPUT THE i VALUE

The value for the i^{th} change of second variable.

RUN WITH NOISE Y=0 N=1

Run with the noise sources or not. Yes = 0 No = 1.

** If response to above is 1, then the program begins a run.

SELECT THE PARTICULAR NOISE INPUTS N=0 Y=1

User has option of keeping all noise sources in the program (0) or selecting which noise sources are to be input (1).

** If response to above is 0, then the program begins a run.

ADD IN INPUT NOISE Y = 0 N = 1

Yes = 0, No = 1.

TABLE 33. CONTINUED

ADD IN SHOT NOISE Y = 0 N = 1

Self explanatory.

ADD IN TRANSFER NOISE Y = 0 N = 1

Self explanatory.

ADD IN THE OUTPUT NOISE Y = 0 N = 1

Self explanatory.

ADD IN THE FILTER NOISE Y = 0 N = 1

Self explanatory.

ADD IN THE TRAP NOISE Y = 0 N = 1

Self explanatory.

** Program begins a run.

TABLE 34. QUESTIONS ASKED BY THE LINEAR FM FILTER SIMULATION

CREATE NEW FILE ON DAT SLOT +2 Y = 0 N = 1

If user wants the output saved for later use, response should be a 0. If not, then a 1. The data will be stored on file TEMPØ2.DAT for a response of 1.

NAME OF FILE XXXXXX.DAT

If response to above was a 0, then user must give the name of the file. Only restrictions are that the file cannot begin with a numeric and all spaces must be filled in with a character or a blank.

THE NUMBER OF STAGES IN CCD (F10.0)

User specifies the number of stages from 1 to 600. The upper limit is only restricted by core size.

SD OF THE INITIAL STATE (F10.0)
IF < Ø, THEN NO BACKGROUND VOLTAGE ADDED

The user specifies the number of electrons for the standard deviation of the initial state of the CCD. If a negative number is given, the system will not add in background charge to the input signal.

NOISE + TARGET Ø
NOISE 1
TARGET 2

The user response with the input configuration. A = Ø, the user wishes a target and noise as an input. If response is a 1, only noise injected at input and finally, if response is a 2, then only a target with no noise at input to CCD.

SURFACE OR BURIED (0 OR 1)

The user specifies a 0 for surface device and a 1 for buried device.

AREA OF THE WELL IN MIL**2

The user specifies the area of each gate.

% OF BACKGROUND CHARGE
< Ø, THEN SPECIFY TRANSFER LOSS

The user specifies the % of background charge which determines the charge transfer inefficiency. If the number specifies is less than Ø, then the next question will ask for the loss.

TABLE 34. CONTINUED

FRACTION LOSS EACH TIME .XXXX

If the response to the above question was negative, then the user specifies the fraction loss on each transfer.

CLOCK SWING VOLTAGE

The user specifies the clock swing voltage of the device.

PLOT OF INPUT AND OUTPUT Y=0 N=1

If user wants a plot of input and output signals, response is a zero. If not, then a 1.

HAMMING WEIGHTING TO OUTPUT Y=0 N=1

If user wants Hamming weighting applied such that the time sidelobes are suppressed, then a 0 is response. If not, then a 1.

FFT OF OUTPUT Y=1 N=0

User responses with a 0 if no FFT of output is wanted and with a 1 if it is wanted.

CLOCK FREQUENCY (F10.0)

User responds with the sampling frequency of the device.

THE LENGTH OF TIME OF THE RUN < 1201

The number of samples from the input signal that are processed by the CCD.

PRINT OUT INTERMEDIATE VALUES NO=0 YES=1

For debugging purposes, the user has the option of examining the contents of the wells.

FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1

A DC component corresponding to feedthrough voltage is added if response is a 1. If a Ø, none is added.

DURATION OF THE SIGNAL MIN=0 MAX=1200

The number of samples of the input which will contain a signal versus number of samples with no signal. The signal samples are centered about the middle of the sampling window.

TABLE 34. CONTINUED

BANDWIDTH OF THE LINEAR FM (HERTZ)

The bandwidth of the linear FM signal is specified by the user in hertz (< sampling frequency bandwidth).

SIGNAL TO NOISE RATIO AT IF (dB)

The user specifies the signal to noise ratio of the target at input to the device.

PHASE ANGLE OF TARGET DEGREES

The user specifies the phase angle of the target in degrees (0-360).

DC BIAS (% OF WELL) TERM ADDED TO INPUT F10

User responds with a DC bias added to input signal in terms of % of a full well.

MEAN ERROR IN TAP WEIGHTS

User specifies the mean tap weight accuracy.

SD OF THE TAP ERROR

User specifies the standard deviation about the above mean value.

AMBIENT TEMPERATURE IN DEGREES °C

User specifies the ambient temperature that the device will operate at.

DARK CURRENT ADDED Y=0 N=1

Dark current added Yes = 0 No = 1.

MULTIPLE RUN Y=# OF CHANGES N=0

User has option of changing a parameter between runs. If response is > Ø, then number of runs with this variable changed. If Ø, then none.

** If response to above is Ø, then the next 5 questions are omitted.

WHICH INPUT IS TO BE CHANGED
1 = NUMBER OF STAGES, 2 = SD OF THE TAP WEIGHTS
3 = AREA OF WELL, 4 = MEAN OF THE TAP WEIGHTS
5 = CLOCK FREQUENCY, 6 = AMBIENT TEMPERATURE

User response is the variable to be changed.

TABLE 34. CONTINUED

INPUT THE i VALUE

Response is to input the value for the i^{th} run.

SECOND VARIABLE CHANGING Y = NUMBER N = 0

Response is the number of times the second variable is to be changed. If Ø, then none.

** If response to above Ø, then skip next 2 questions.

WHICH INPUT

The variable number to be changed.

INPUT THE i VALUE

The value for the i^{th} change of second variable.

RUN WITH NOISE Y=0 N=1

Run with the noise sources or not. Yes = 0 No = 1.

** If response to above is 1, then the program begins a run.

SELECT THE PARTICULAR NOISE INPUTS N=0 Y=1

User has option of keeping all noise sources in the program (0) or selecting which noise sources are to be input (1).

** If response to above is 0, then the program begins a run.

ADD IN INPUT NOISE Y = 0 N = 1

Yes = 0, No = 1.

ADD IN SHOT NOISE Y = 0 N = 1

Self explanatory.

ADD IN TRANSFER NOISE Y = 0 N = 1

Self explanatory.

ADD IN THE OUTPUT NOISE Y = 0 N = 1

Self explanatory.

ADD IN THE FILTER NOISE Y = 0 N = 1

Self explanatory.

TABLE 34. CONTINUED

ADD IN THE TRAP NOISE Y = 0 N = 1

Self explanatory.

** Program begins a run.

5.2 SIMULATION OPERATIONAL CAPABILITIES

The simulation was designed to model the transfer of electrons from stage to stage in a CCD delay line. The simulation accomplishes this by transforming an input voltage to an electron packet. The packet is then moved through the various stages of the device with the appropriate noise perturbations added to the packet of charge at each clock pulse. The noise sources that have been incorporated in the model are the input, output, trap, shot, transfer and filter coefficient inaccuracies. Dark current has also been incorporated in the model. The noise sources have been made functions of device (surface or buried), area, clock voltage, clock frequency, temperature.

The simulation has the capabilities of operating in two modes: delay line and tapped delay line. The delay line can be operated in either a continuous mode or a storage mode. The continuous mode corresponds to clocking the data through the device at one clock rate. The storage mode corresponds to clocking the data into the device, storing for a given length of time and then clocking the data out.

These modes enable a user to simulate a single device, such as a delay line, FIR filter or more complex devices such as chirp filters or doppler filter banks by interconnecting the simple devices by relatively minor programming connections of the individual modules of the computer programs. This would thus enable the user to test the critical parameters of a CCD in a system with relative ease.

6.0 SIMULATION RESULTS

6.1 DELAY LINE TESTS - STORAGE AND CONTINUOUS MODES

6.1.1 Effects of Charge Transfer Inefficiencies on Device Non-Linearities

The Charge Transfer Inefficiency (CTI) leaves behind at each transfer a packet of charge which is signal dependent. In the simulation model this CCD characteristic was modeled as a percentage of the charge being subtracted off from the charge packet which is being transferred from well to well. Transferred electrons = electrons to be transferred - the percent of the electrons being transferred, and the electrons left behind (residue) = the percent of the electrons being transferred. The possible non-linear distortions of the CTI on a signal were examined by inputting a 1500 Hz sine wave with a 1.3 volt amplitude riding on a 1.4 volt bias. A full well of the CCD has a corresponding voltage of 2.8 volts. The peak value of the input signal is approximately 97% of a full well. The length of the CCD line was 310 stages with operating characteristics of 6 KHz clock, a gate area of 2 mil^2, a clock swing voltage of 10 volts, and a temperature of 27°C. The dark current and the other noise sources were not added. Figure 55 is a plot of the Hamming weighted power spectrum of the CCD's output. An extreme value of the CTI (1×10^{-3}) was used. As can be seen in Figure 55, the harmonics generated are more than 100 dB down from the peak representing 1.5 KHz. (In all the following figures, the curves on the power spectrums were normalized to the peak of that curve.) The sharp spike in Figure 55 is caused by the Hamming weighting which spreads the DC term thus not allowing complete cancellation when the mean is subtracted before finding the power spectrum. (In Figures 55 and 56, the 128 frequency sample corresponds to the sampling rate.) In conclusion, since the level of non-linear distortion observed in Figure 55 is so low for even an extreme value of the CTI, the CTI can be ruled out in the model as a possible contributor to non-linear distortions.

6.1.2 Non-Linear Effects of Dark Current

Having observed that the CTI does not contribute to the non-linearity of the device, the remaining possible contributor in the model is the dark current. The dark current distortion would arise when the signal is clipped due to the potential wells filling up with dark current. The effect of clipping should be analogous to amplitude clipping in a limiter. To examine the possible distortions, a 7 Hz sine wave with a 1.3 volt amplitude riding on a 1.4 volt bias (full well corresponds to 2.8 volts) was inputted into a 600 stage CCD delay line. The operating characteristics of the device were a clock swing voltage of 10 volts, a temperature of 27°C, and a gate area of 2 mil^2. The CTI was set equal to zero (no loss due to charge transfer inefficiency) and the noise sources were not added in. The sampling rate of the device was 30 Hz which corresponds to each sample of the input being in the device for 20 seconds. Figure 56 is a plot of the power spectrum of the output with Hamming weighting. As can be seen from Figure 56, the second harmonics were approximately only 13 dB down from the peak spectrum component at 7 Hz. (As in Figure 55, the Hamming weighting spread the DC term thus not allowing full cancellation; and the spike near DC is the result). Thus, the distortions due to dark current can become severe if clipping is allowed to

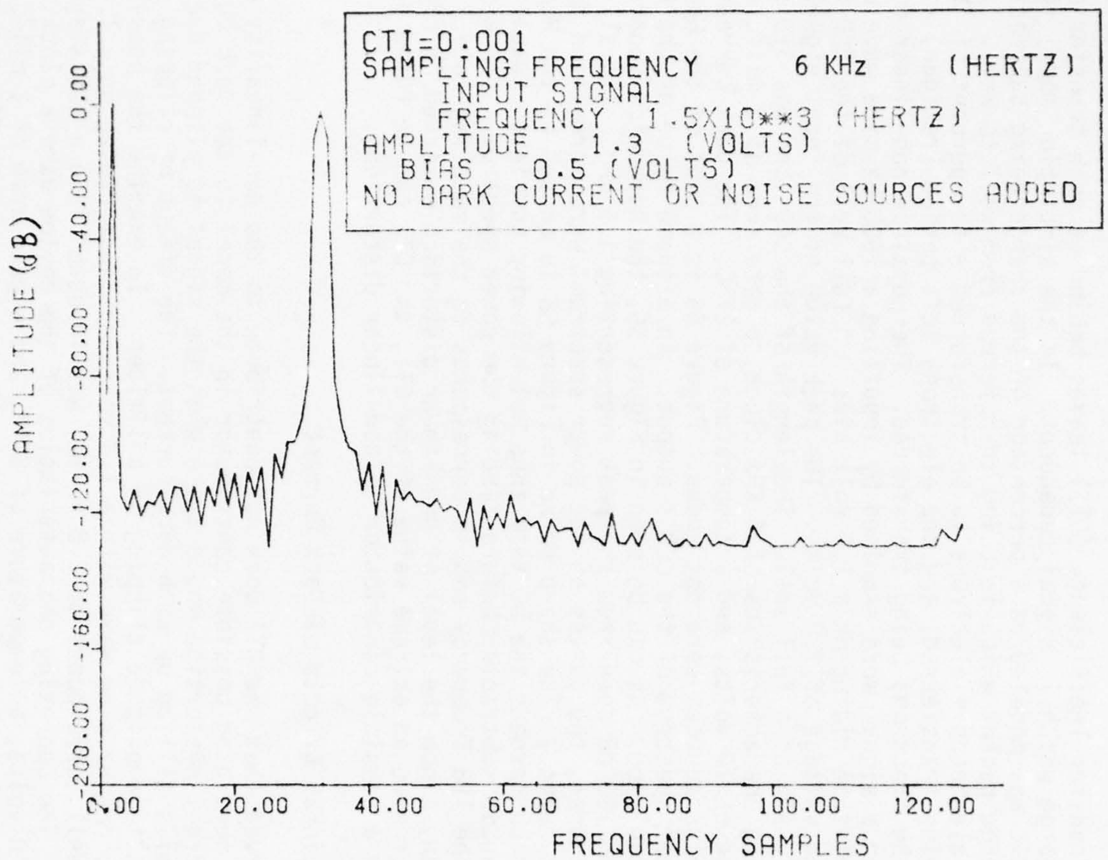


FIGURE 55. AMPLITUDE VERSUS CLOCK RATE OF THE OUTPUT OF A CCD DELAY LINE WITH A SINUSOIDAL INPUT FOR A LARGE CHARGE TRANSFER INEFFICIENCY (CTI = 0.001)

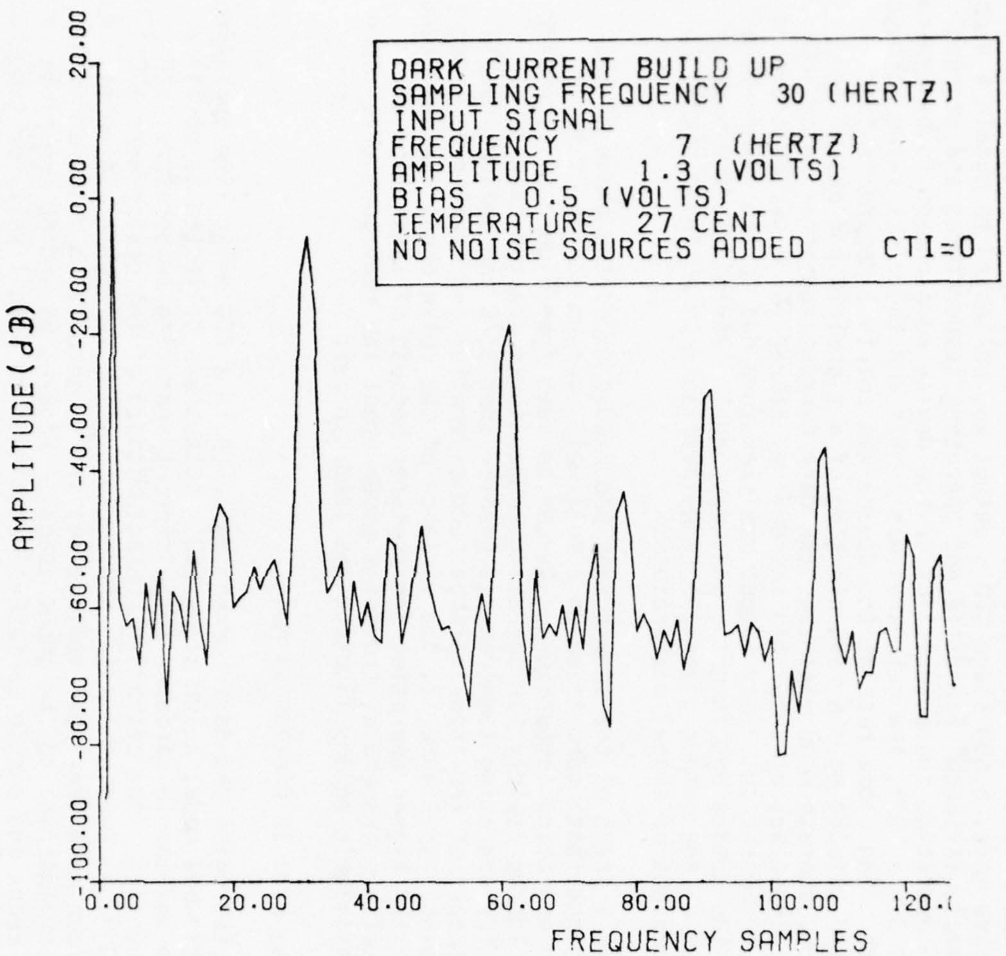


FIGURE 56. AMPLITUDE VERSUS CLOCK RATE OF THE OUTPUT OF A CCD DELAY LINE WITH A SINUSOIDAL INPUT WITH DARK CURRENT BUILD-UP

occur. The degree of clipping and its frequency is related to the operating parameters of the device and the input signal. In the discussion below, the operating parameters are examined.

6.1.3 Delay Line In Storage Mode

To examine the effects of noise and dark current build-up in a CCD delay line in the storage mode, a 600 stage CCD's output was collected to obtain a sample mean and sample variance* for different operating temperatures and storage times. The operating characteristics of the device were chosen to be typical. The CTI was 3.6×10^{-4}, the gate area was 2 mil^2 and the clock swing voltage was 10 volts. The clock rate of the device was set to 1 Megahertz for inputting and outputting. A fast clocking of a signal in and out of the device in the storage mode minimizes the dark current and other noise sources. A zero volt input was clocked into the device, stored for a variable amount of time, and clocked out. Any output was therefore due to the internal noise sources of the device and is not signal dependent. Therefore, the measure of the noise at the output gives the range available to an input signal for different amounts of signal distortions.

Figure 57 is a graph of the sample mean and Figure 58 is the graph of the sample variance (both normalized to a full well) versus storage time in seconds and operating temperature. As can be seen from Figure 57, the dark current builds up rapidly for operating temperatures greater than 35°C. Therefore, for operating temperatures greater than 35°C the maximum usable amplitude (peak) of the input voltage becomes smaller and smaller in order to avoid clipping. In Figure 58, the variance of the noise about the mean tends to zero for the higher operating temperatures because of saturation of potential wells. Therefore, the noise power about the mean goes zero since the range available to any fluctuations tends to zero.

6.1.4 Delay Line In Continuous Mode

To examine the noise and dark current build-up in a CCD delay line operating in the continuous mode, a 128 stage CCD's output was collected to obtain a sample mean and sample variance for different operating temperatures and clock frequencies. The operating characteristics of the device were a CTI of 3.6×10^{-4}, an area of 2 mil^2, and a clock swing voltage of 10 volts. As in the storage mode the input voltage was set to zero (zero volts added at each sampling interval to the input stage). Figures 59 and 60 are plots of the sample means and sample variances normalized to a full well for temperatures in the range of -55°C to +125°C and clock frequencies of 5 to 5×10^5 Hz. As

---

* Sample Mean = $\sum_{i=1}^{N} x_i/N$ where x_i are the data samples and N is the number to be averaged.

Sample Variance = $\sum_{i=1}^{N} (x_i - \overline{X})^2/(N-1)$ where x_i and N are same as for sample mean and $\overline{X}$ is the sample mean defined above.

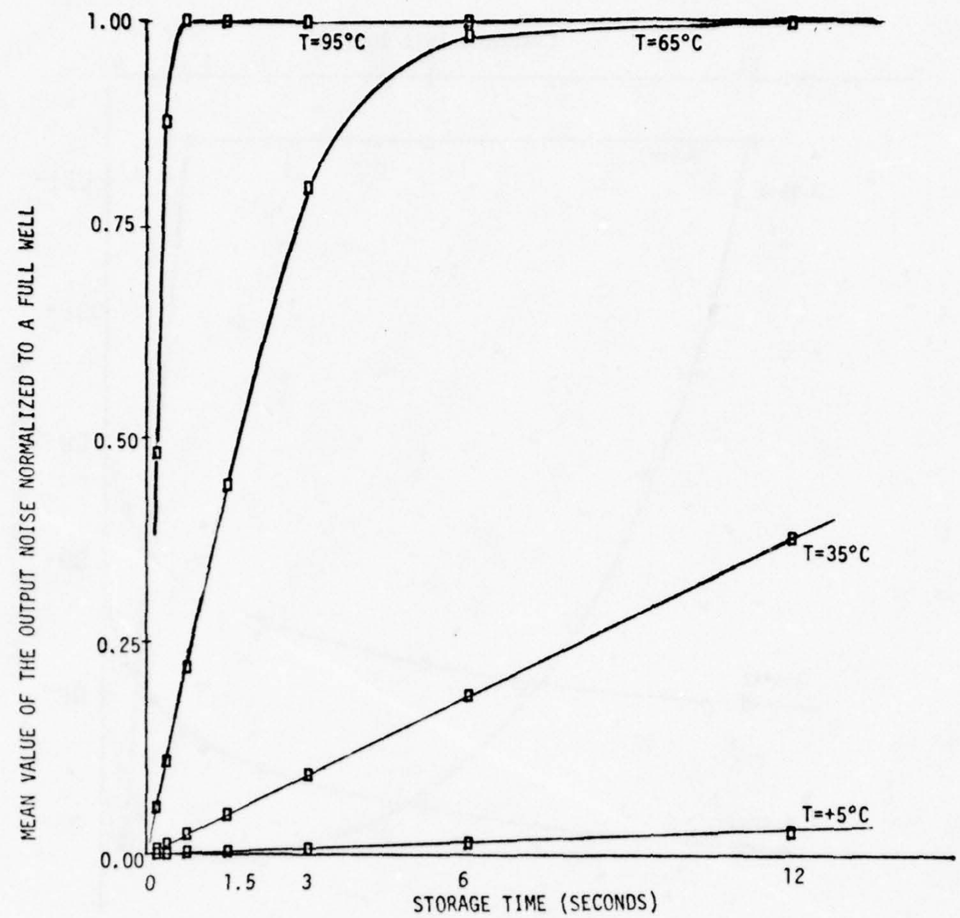


FIGURE 57. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS STORAGE TIME VERSUS TEMPERATURE FOR A CCD DELAY LINE IN STORAGE MODE

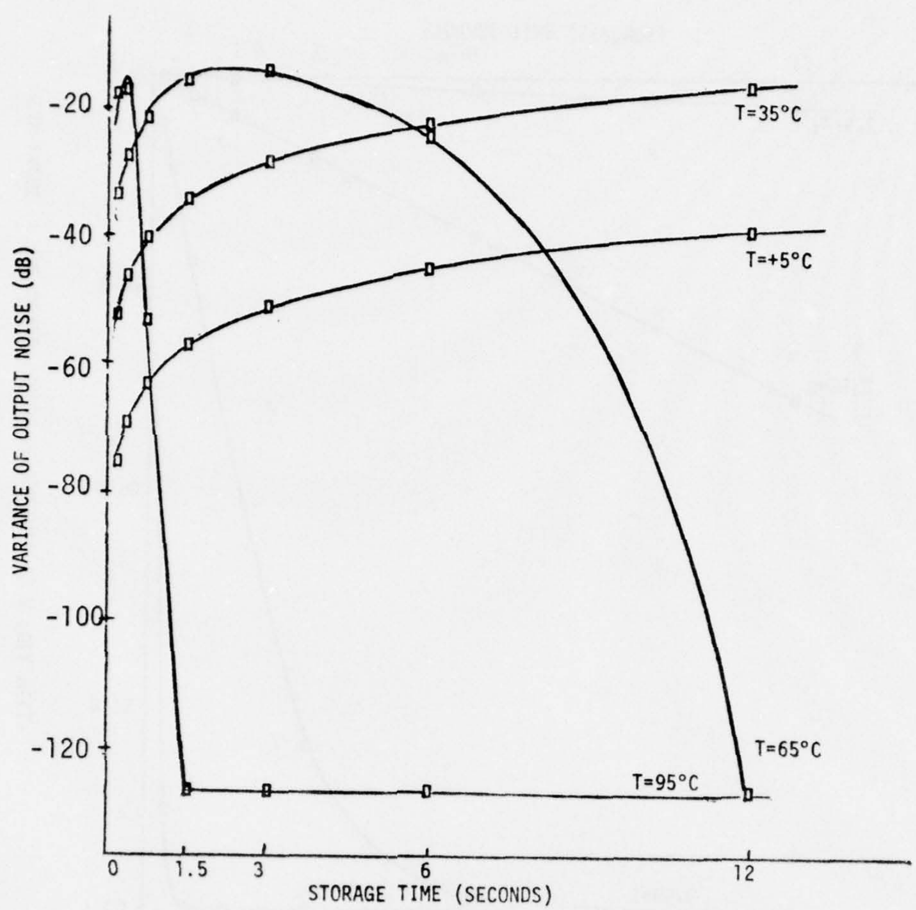
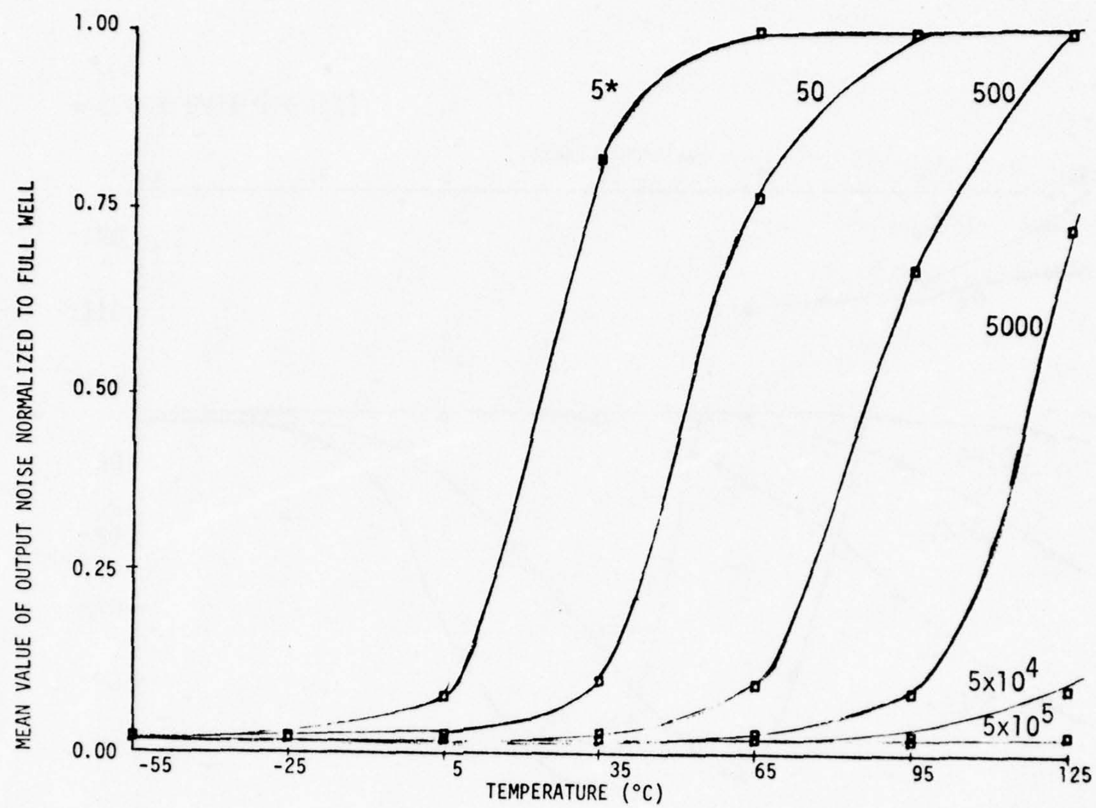


FIGURE 58. VARIANCE OF THE OUTPUT NOISE VERSUS STORAGE TIME VERSUS TEMPERATURE FOR A CCD DELAY LINE IN STORAGE MODE



* CLOCK RATE (HERTZ)

FIGURE 59. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS TEMPERATURE VERSUS CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

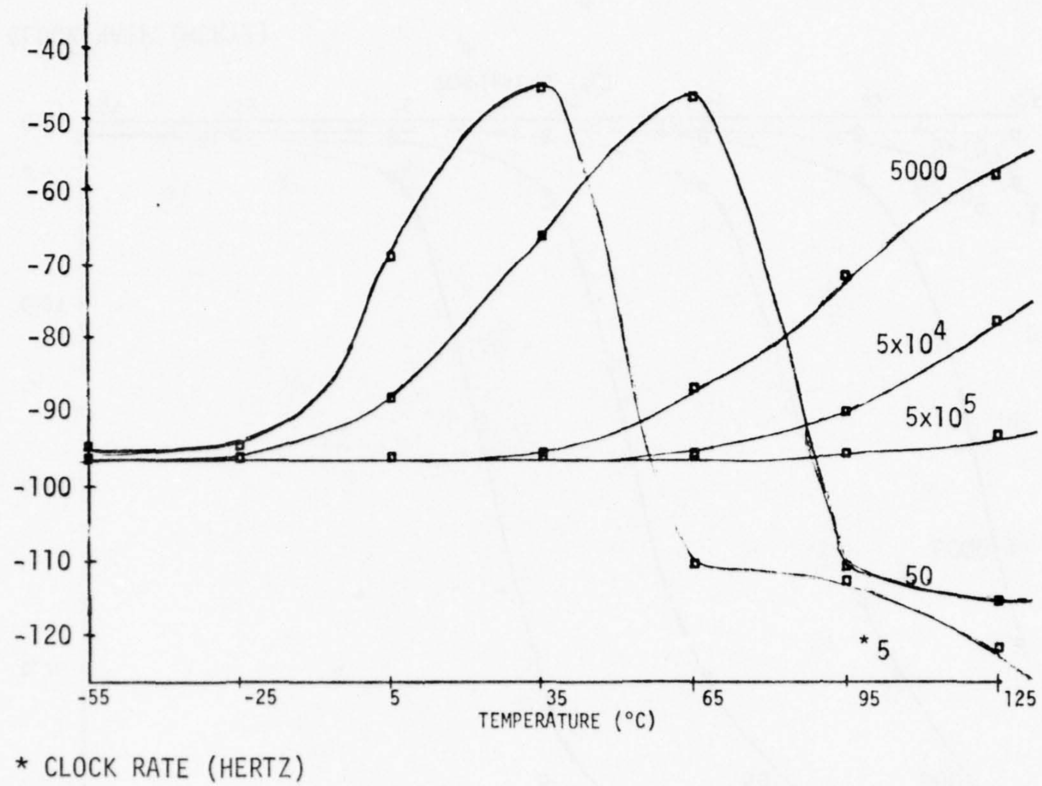


FIGURE 60. VARIANCE OF OUTPUT NOISE VERSUS TEMPERATURE VERSUS CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

observed in the storage mode, the dark current and noise builds up to occupy the full well which causes the variance to go to zero. For a given set of parameters, the variances for the continuous mode are not as large as the storage mode. This is due to the dark current contributions in the continuous mode being averaged over a large number of independent wells while in the storage mode each output sample contains the dark current build-up of a different well.

6.1.5 Number of Stages, Temperature and Clock Rate

To examine the noise and dark current build-up in a CCD delay line operating in the continuous mode for different number of stages and clock rates, the output was collected and the sample mean and variance were computed for a CCD operating at a temperature of 27°C, CTI of 3.6×10^{-4}, an area of 2 mil^2, and a clock swing voltage of 10 volts. As in the discussion above, zero input voltage was added to the input structure. Figures 61 and 62 are plots of the sample mean and variance normalized to a full well for delay lines of length 16 to 512 and clock frequencies from 50 to 50,000 Hz.

As can be seen from Figure 61, at low clock frequencies, the clock rate must be increased in order to maintain a given noise level for the same number of stages. This effect holds up to a clock rate of about 1500 Hz for the CCD parameters used.

6.2 LINEAR FM MATCHED FILTER SIMULATIONS

The foregoing simulations have examined the CCD operation as a delay line either in the storage mode or the continuous mode. In order to evaluate the CCD operating as a tapped delay line, the device was configured in a linear FM matched filter system. This called for the simulation of four different tapped delay lines (Figure 63) for the complex I and Q channels of the filter. The coefficients of the delay line were modified with Hamming weighting to reduce the time sidelobes of the output.

In Figures 64 through 108, the number of input samples was 512 with the length of the individual CCD tapped delay lines set at 129. The matched weights on each tapped delay line were modified by Hamming weighting to reduce the time sidelobes. The Time*Bandwidth product was a constant 64.5 in all the figures. That is, the argument of the sine or cosine waveform at each tapped delay line was Bandwidth * $Time^2/2$ * Length of the signal where the length of the signal was 129/clock frequency which gives a Time * Bandwidth product of Bandwidth * 129/clock frequency (Figure 63). The ratio of Bandwidth to clock frequency was fixed in order to keep the desired product of 64.5. The operating characteristics of the devices were 2 mil^2 for gate area and a clock swing voltage of 10 volts.

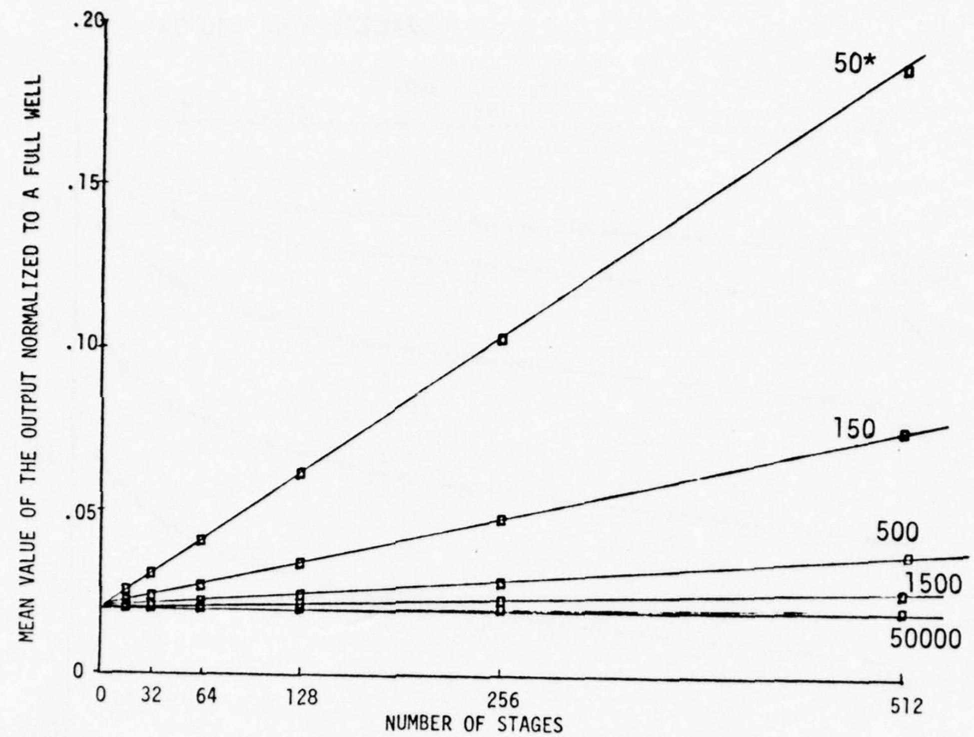
In Figures 66 - 108, the plots are normalized to the peak time response. The reason for including the actual time plots is that in comparing different operating temperatures, clock frequencies, and CTI's on the outputs, the actual data better reflects the degree of spreading and sidelobe levels than a tabular summary.

Figure 64 is a plot of the sidelobe level of the output of the matched filter versus temperature in the ranges of -55°c to 125°C and clock rates from 50 to 150 KHz. The sidelobe level for temperatures less 5°C is fairly constant. However as the temperature is increased, the clock frequency must be increased in order to keep the sidelobe levels down. As can also be observed in the actual time plots, the noise level rises and falls with temperature and frequency. (In Figure 66, the noise is -90 dB from the peak while for Figure 69 it is only -30 dB.)

Figure 65 is a graph of the sidelobe level of the output of the matched filter for coefficient inaccuracies in range of 0 to 10%. The tap weights were allowed to have an error with zero mean and standard deviation of a given percent for a normal distribution. Figure 65 shows that out to 6% there is no system degradation due to tap weight inaccuracy.

Figures 66 through 99 are the outputs from the matched filter for different sampling frequencies and temperatures. The specific case is given in the box on each figure. The plots are normalized to the peak of the time function.

Figures 100 - 108 are plots of the response of linear FM matched filter as Charge Transfer Inefficiency is varied with frequency for a CCD operating at 0°C. (In our model, due to the lack of theoretical and experimental data, we were not able to incorporate CTI as a function of temperature.) Figures 100,113,and 106 show to a marked extent the broadening of the mainlobe and sidelobes of the return. Also observed is the raising of the sidelobe levels and a time shift of the mainlobe when the clock rate is constant while the CTI is varied. These effects are caused by the signal being smeared as it is shifted through the delay line. Finally, as the frequency is increased, no appreciable difference can be observed with regard to width and level of the sidelobes and mainlobe. That is, as frequency is increased, the dark current level decreases, but the effects due to CTI are not diminished.



*CLOCK RATE (HERTZ)

FIGURE 61. MEAN VALUE OF OUTPUT NOISE NORMALIZED TO FULL WELL VERSUS THE NUMBER OF STAGES AND CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

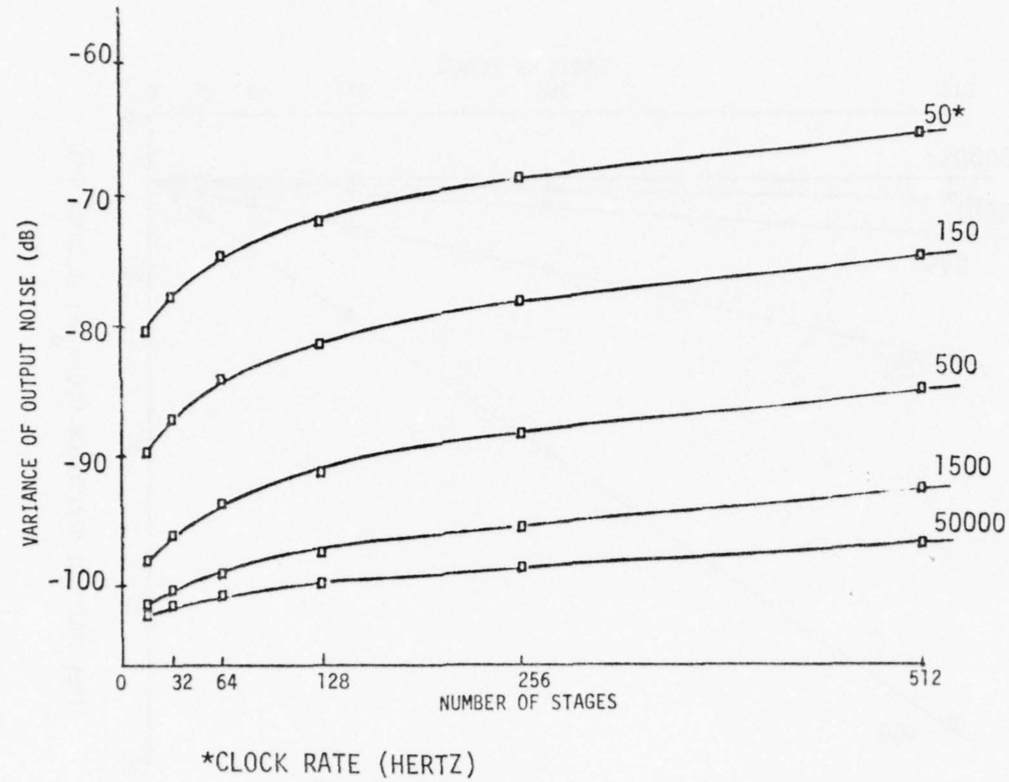
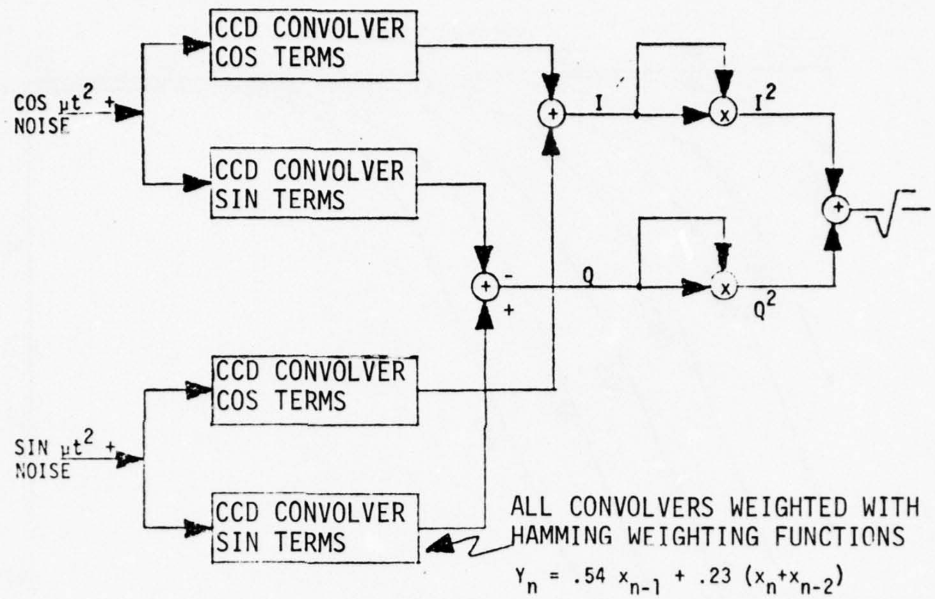


FIGURE 62. VARIANCE OF OUTPUT NOISE VERSUS THE NUMBER OF STAGES AND CLOCK RATE FOR A CCD DELAY LINE IN CONTINUOUS MODE

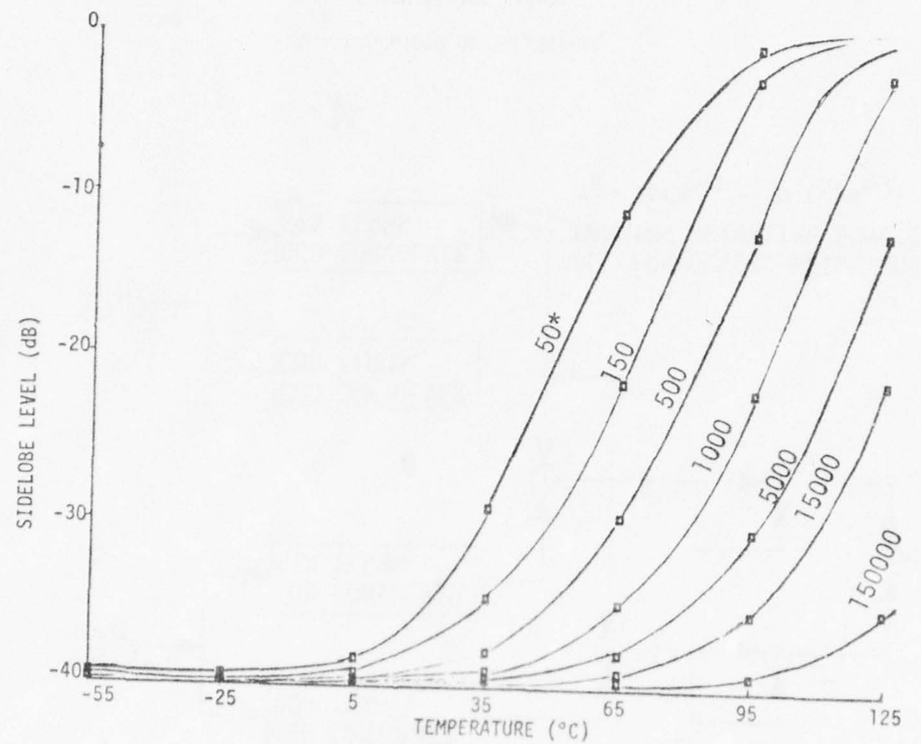


$\mu = \frac{BW}{2T_p}$

BW = BANDWIDTH OF THE SIGNAL

T_p = LENGTH OF THE SIGNAL

FIGURE 63. BLOCK DIAGRAM OF LINEAR FM MATCHED FILTER



*CLOCK RATE (HERTZ)

FIGURE 64. SIDELOBE LEVEL OF LINEAR FM MATCHED FILTER VERSUS TEMPERATURE AND CLOCK RATE

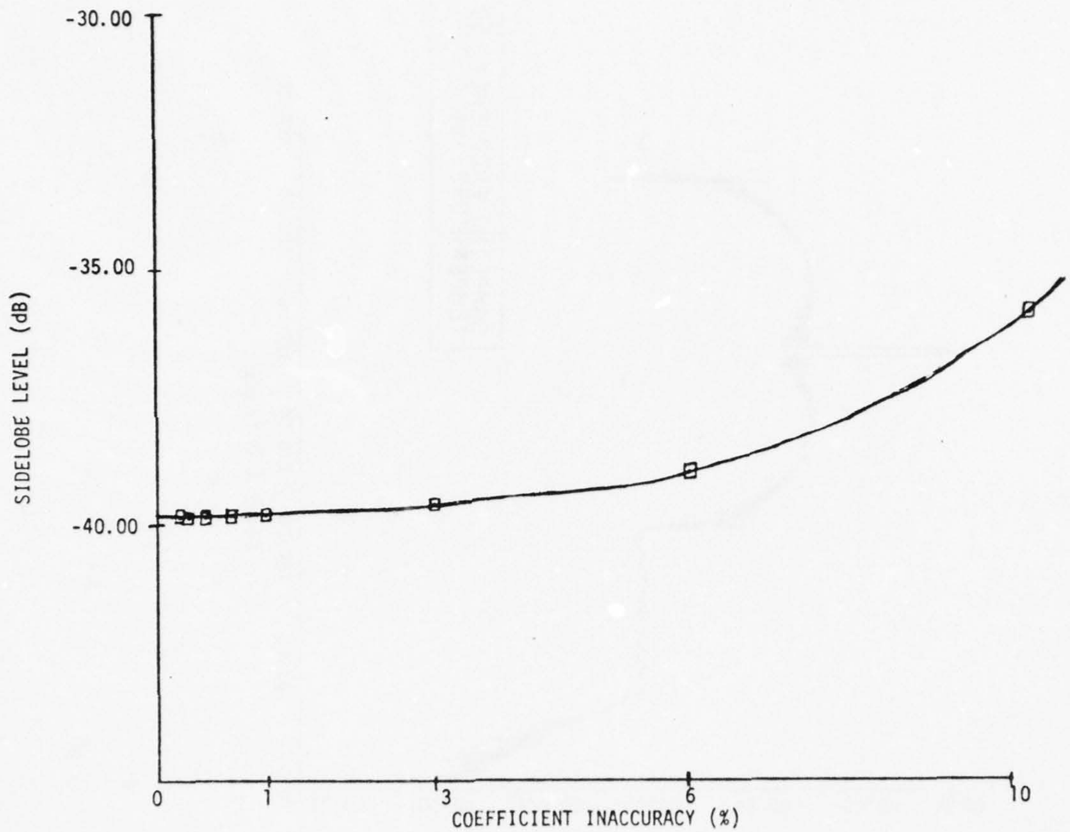


FIGURE 65. SIDELOBE LEVEL OF A LINEAR FM MATCHED FILTER VERSUS COEFFICIENCY INACCURACY

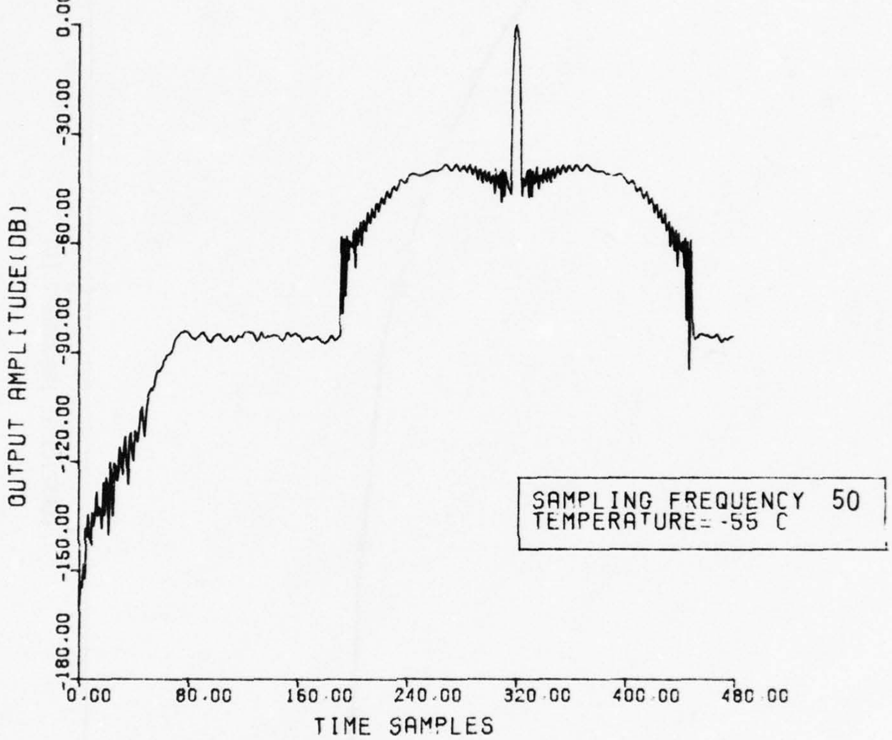


FIGURE 66. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF -55°C

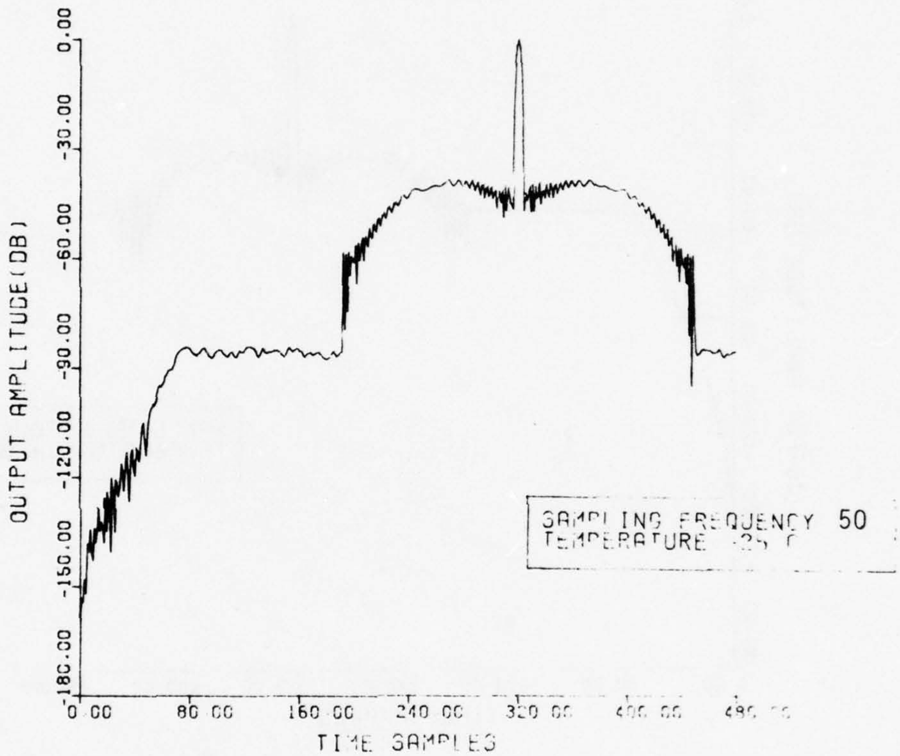


FIGURE 67. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF -25°C

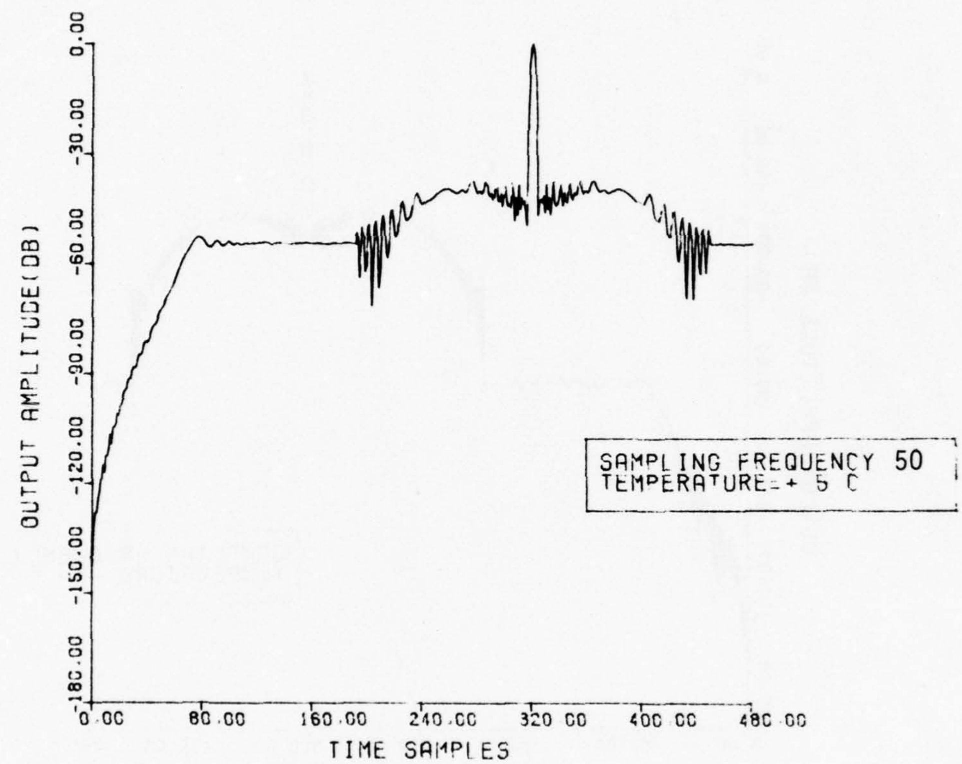


FIGURE 68. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +5°C

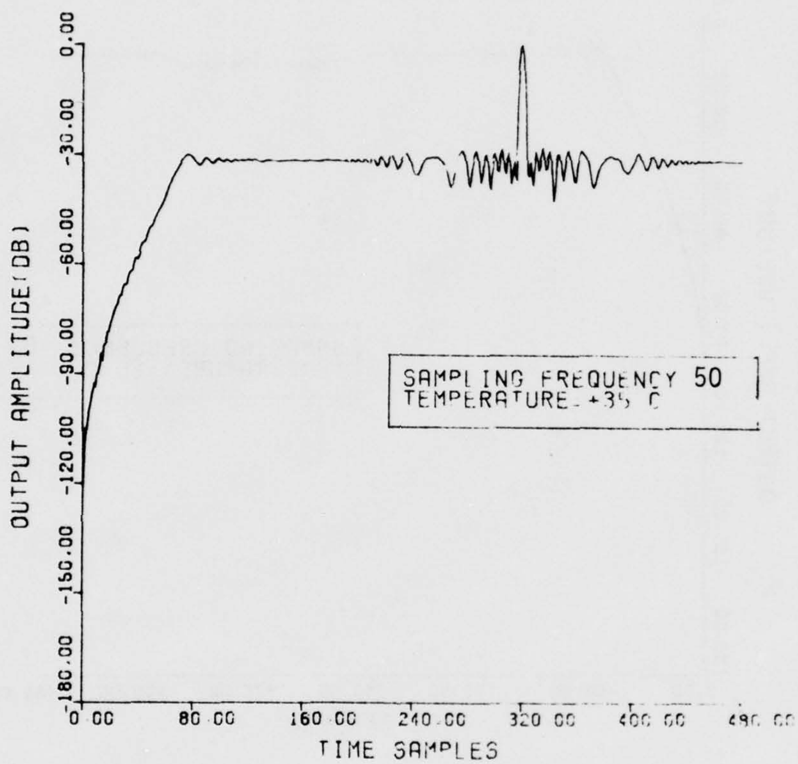


FIGURE 69. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +35°C

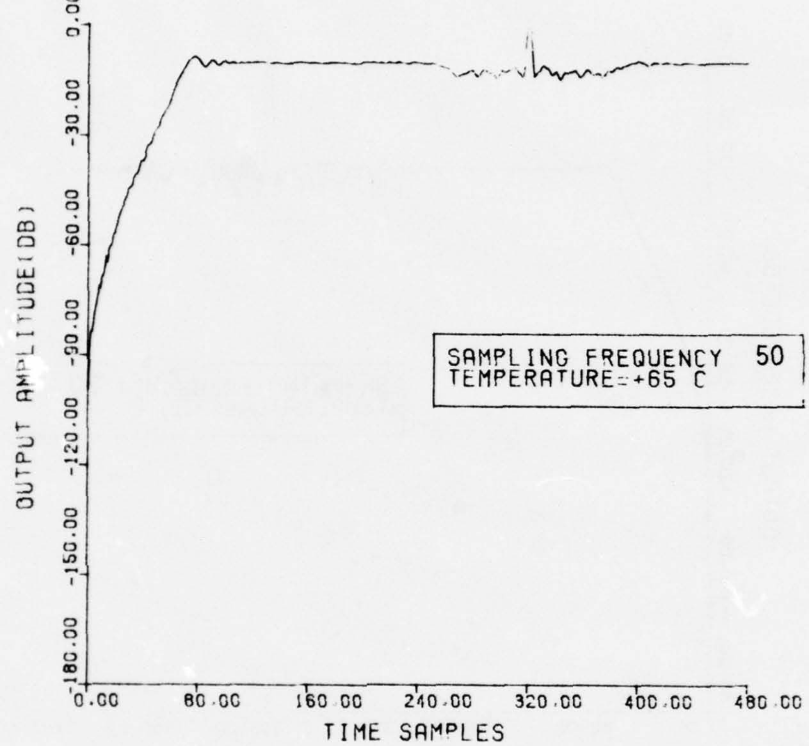


FIGURE 70. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +65°C

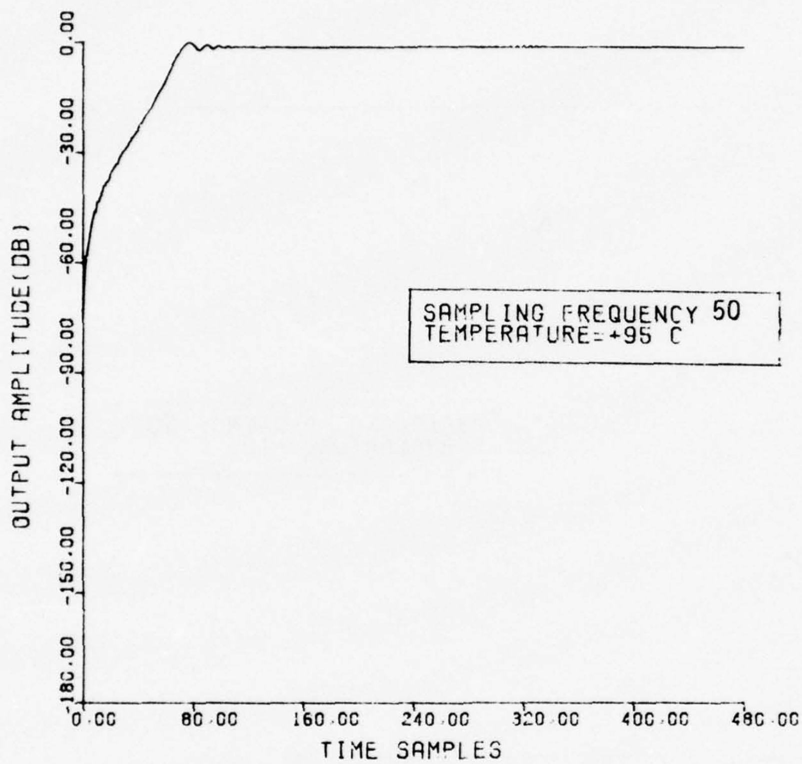


FIGURE 71. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +95°C

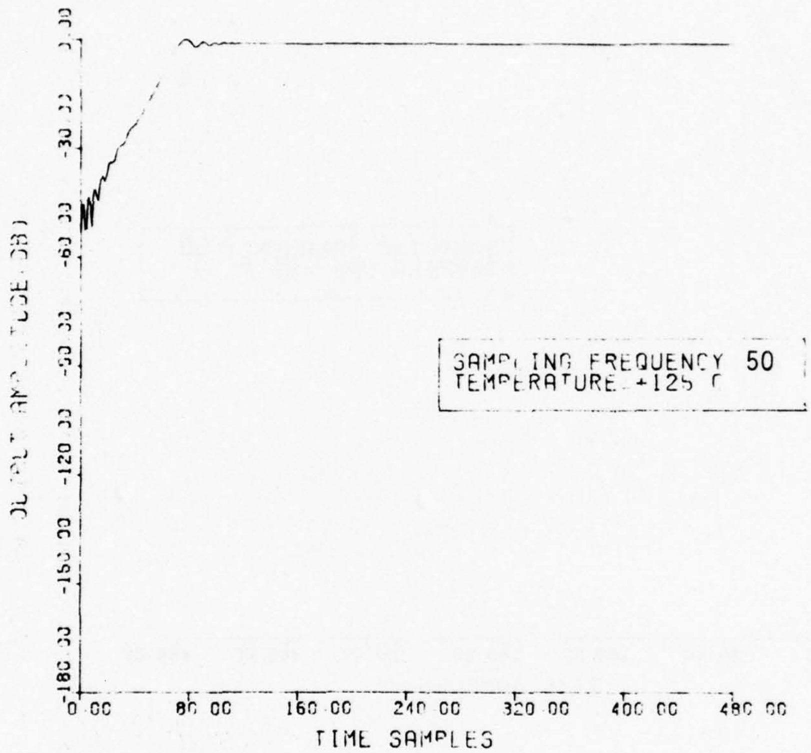


FIGURE 72. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND TEMPERATURE OF +125°C

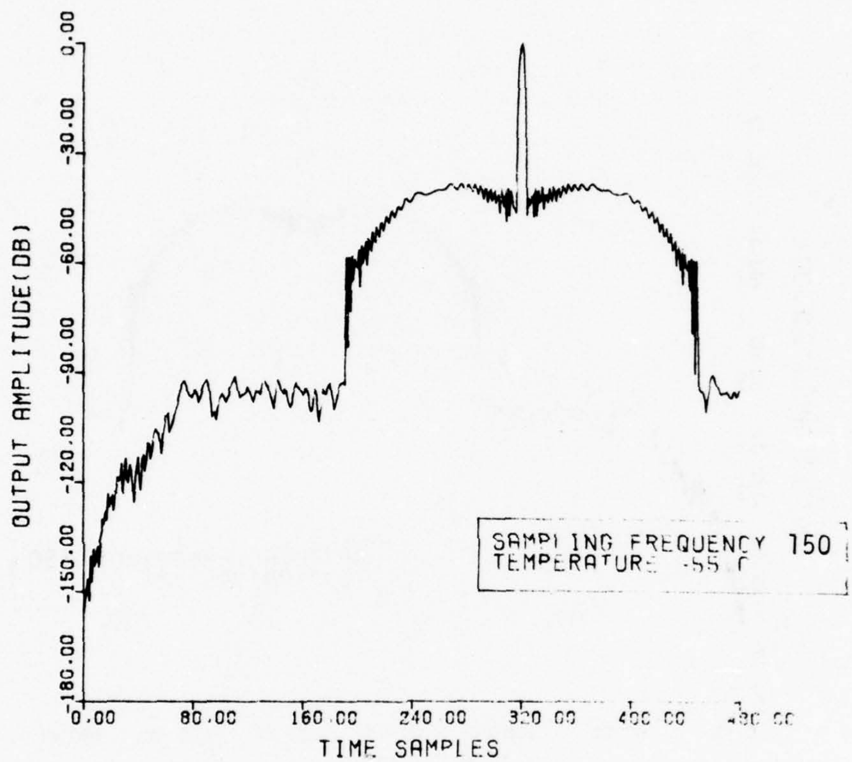


FIGURE 73. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF -55°C

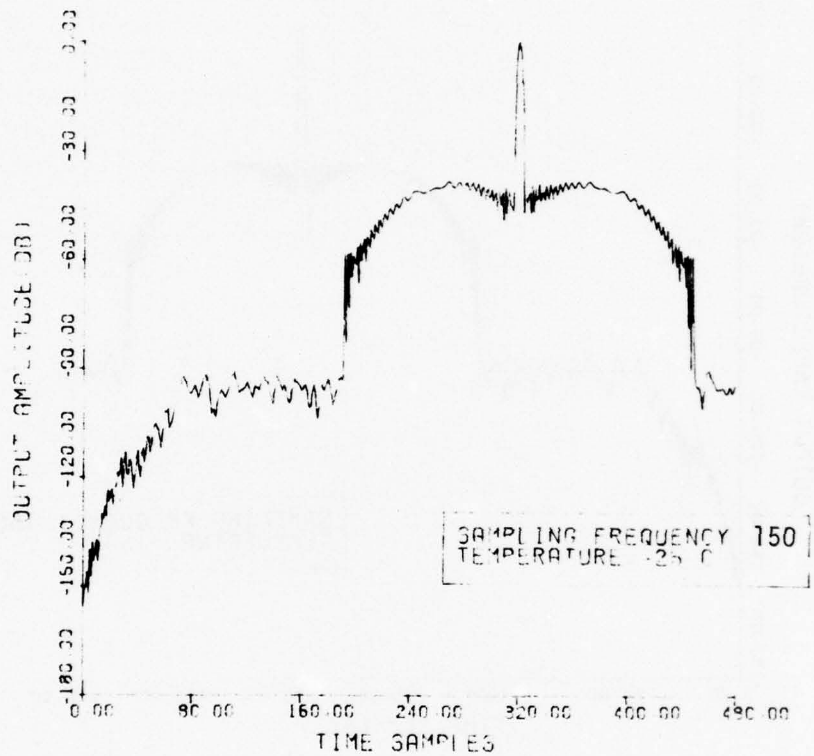


FIGURE 74. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF -25°C

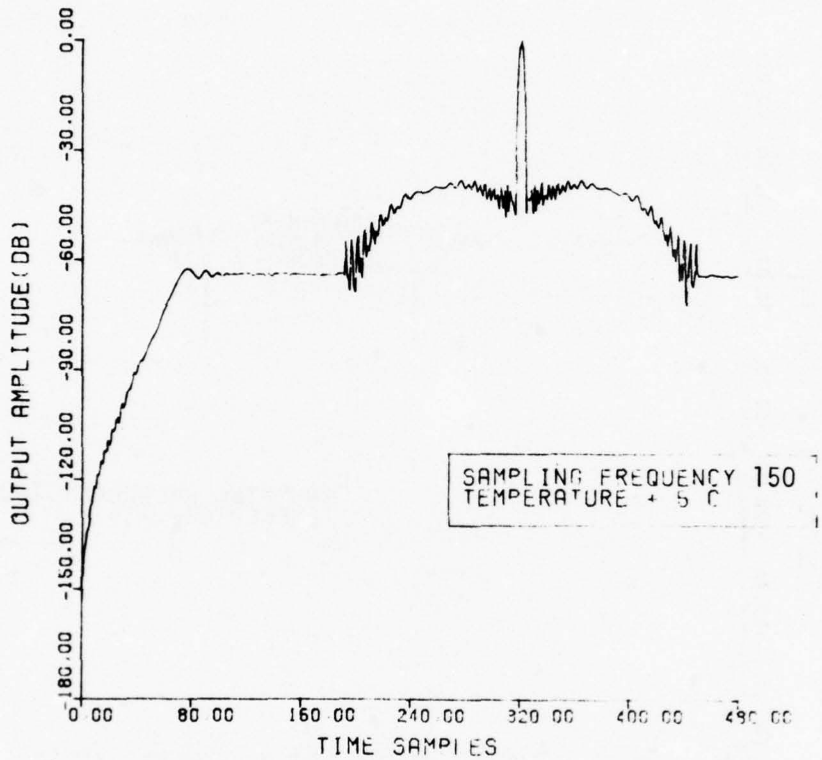


FIGURE 75. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +5°C

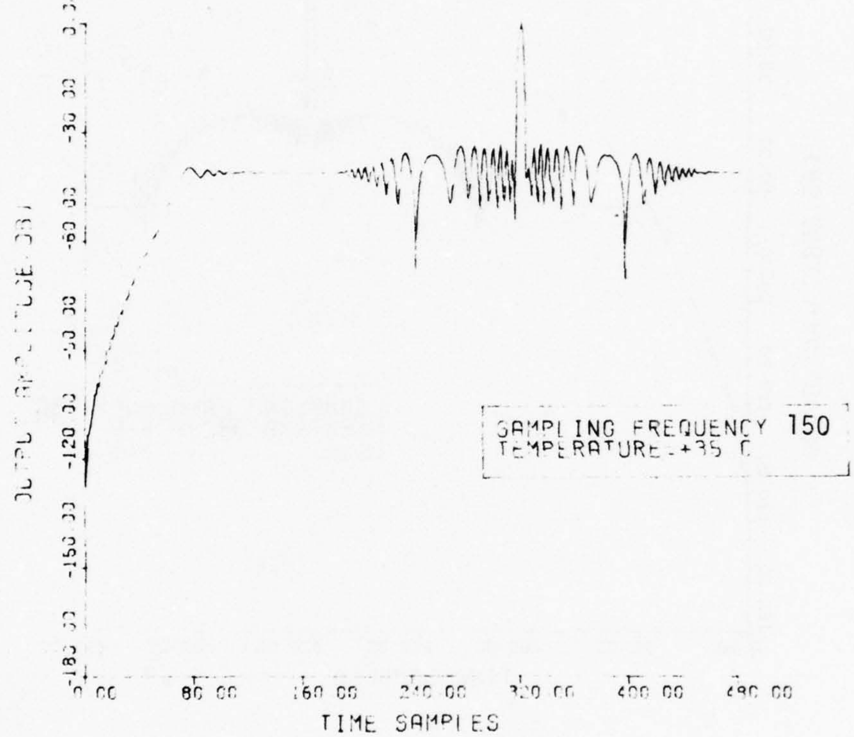


FIGURE 76. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +35°C

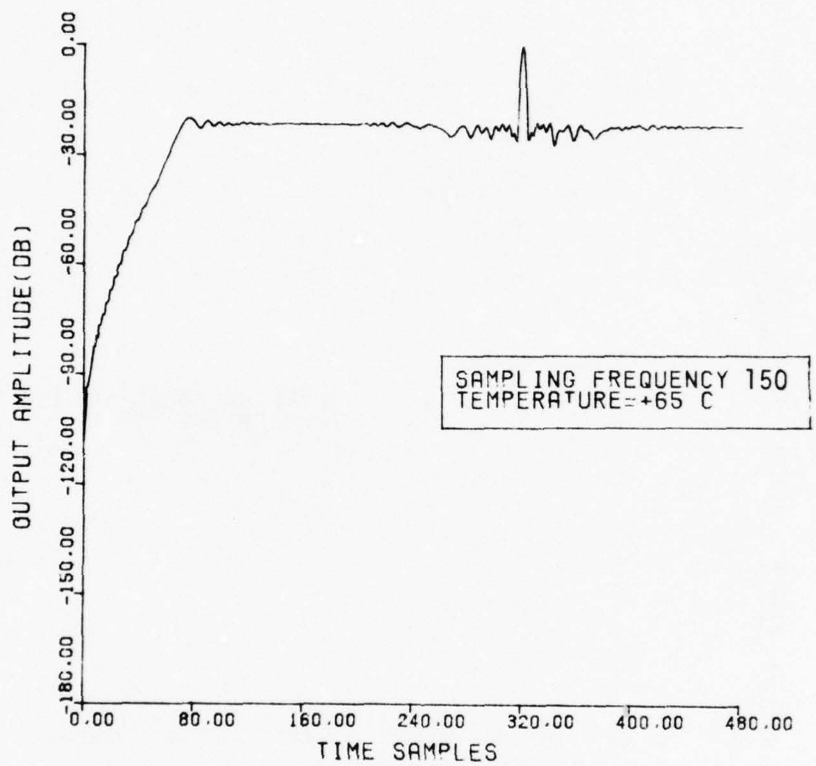


FIGURE 77. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +65°C

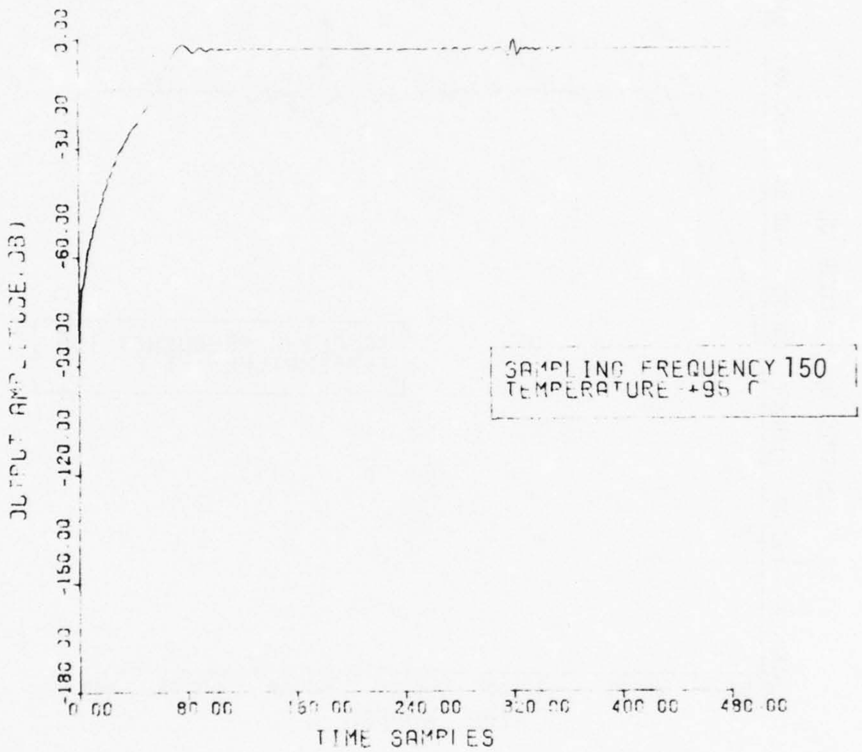


FIGURE 78. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +95°C

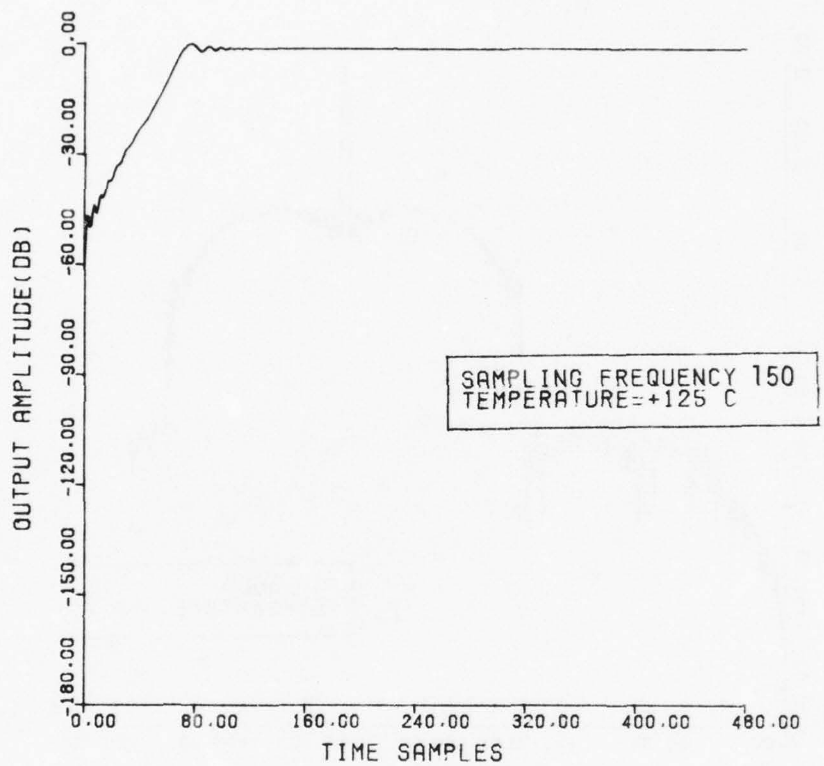


FIGURE 79. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300 HERTZ AND TEMPERATURE OF +125°C

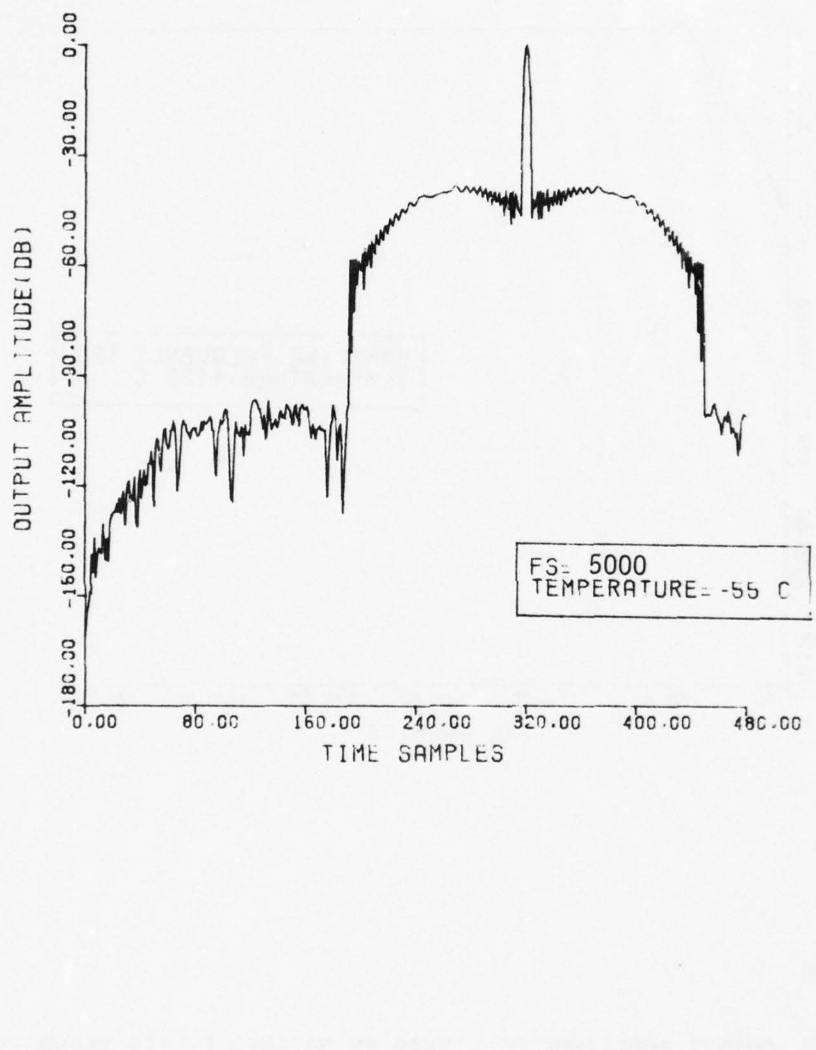


FIGURE 80. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF -55°C

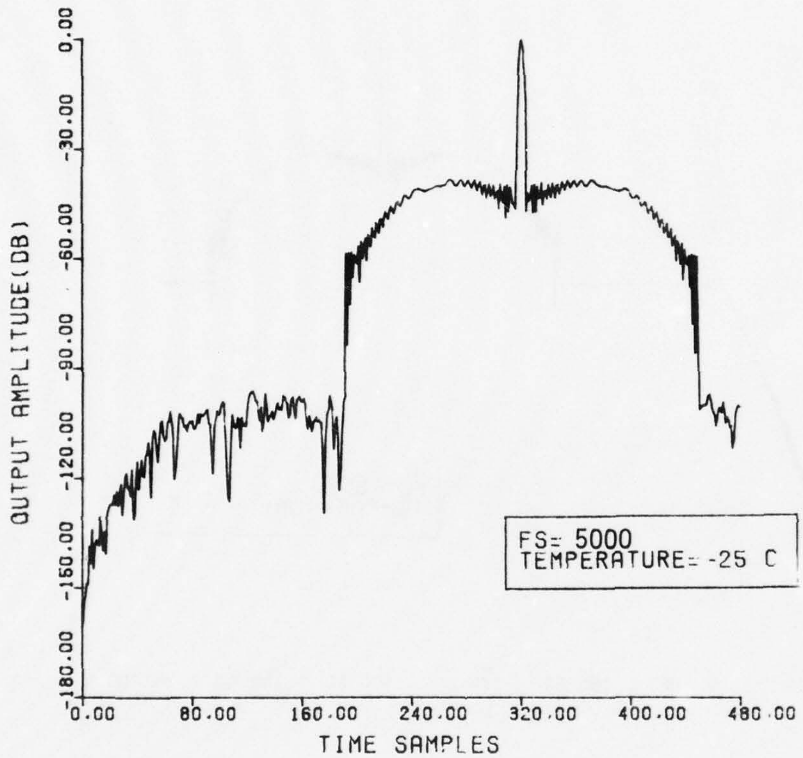


FIGURE 81. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF -25°C

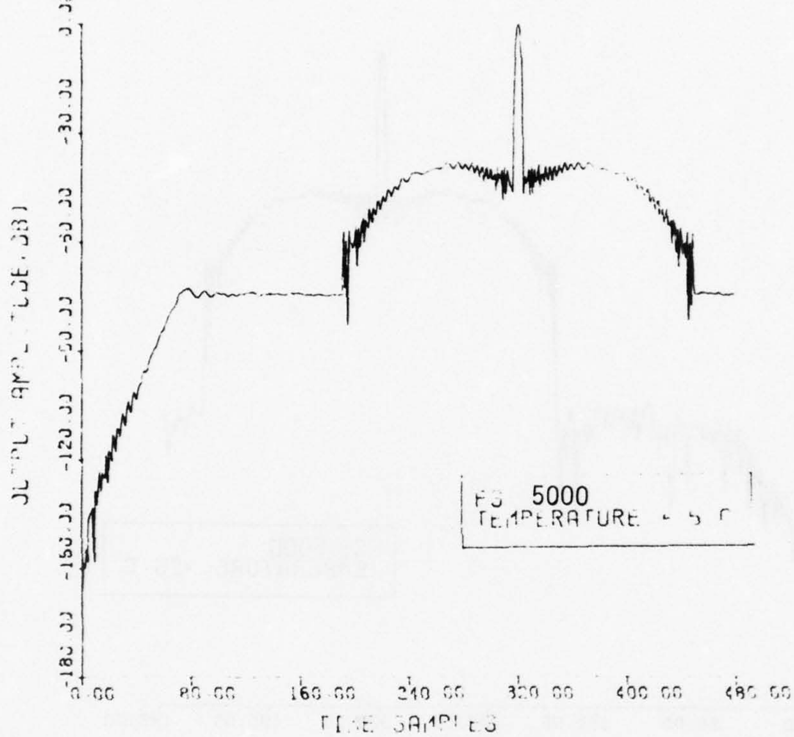


FIGURE 82. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +5°C

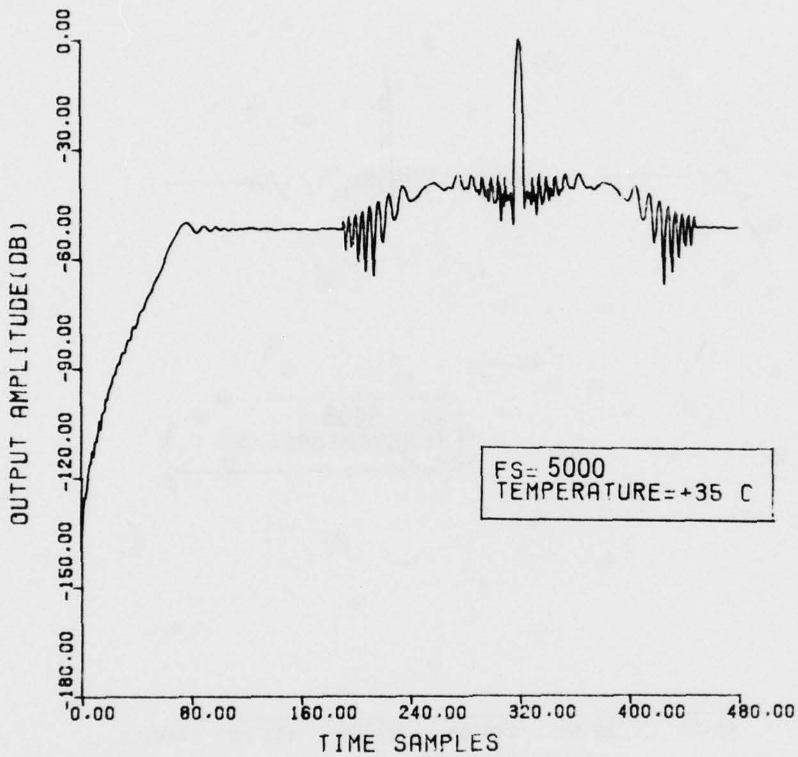


FIGURE 83. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +35°C

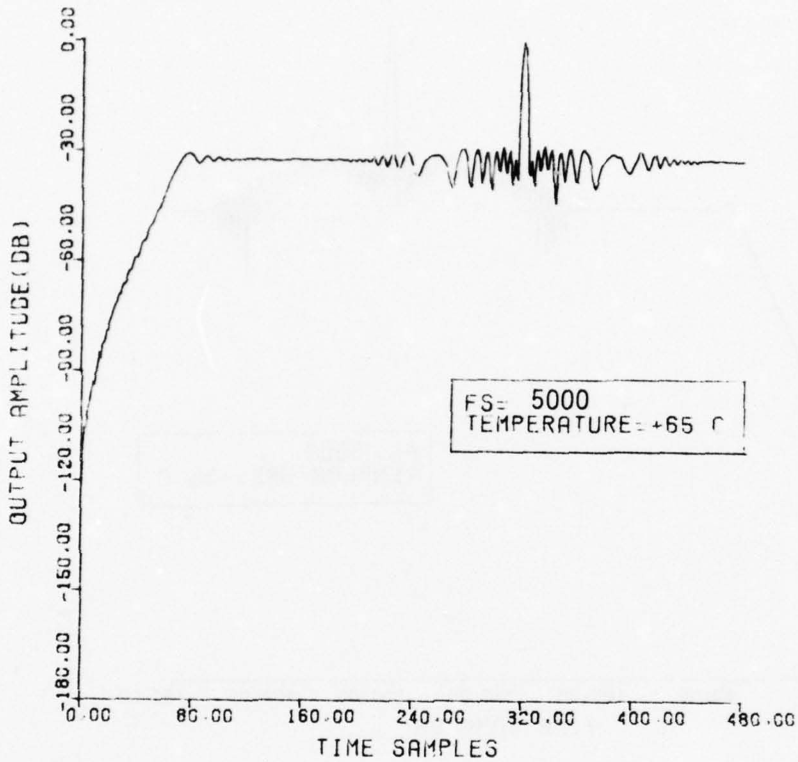


FIGURE 84. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +65°C

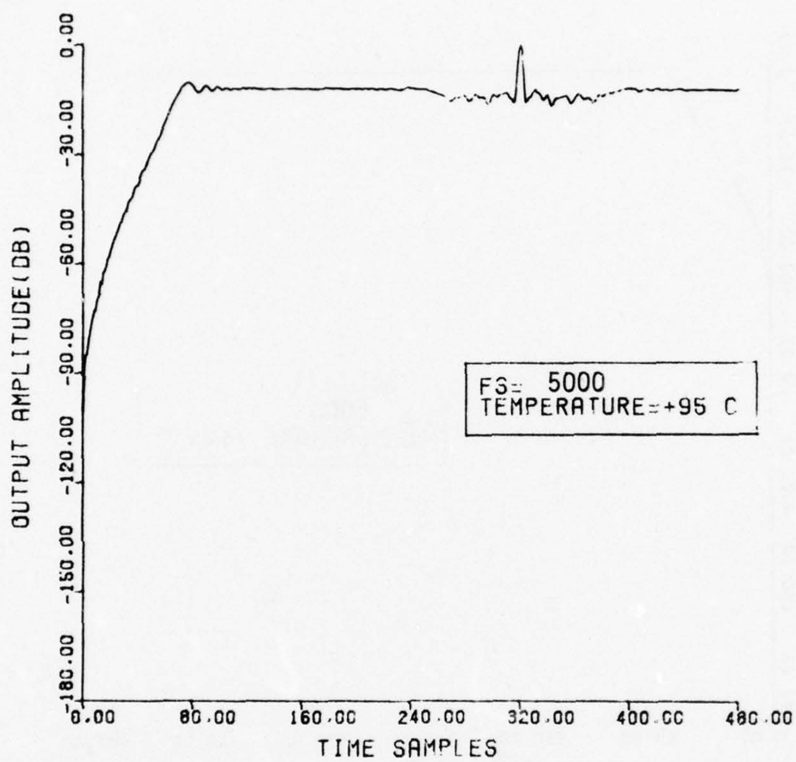


FIGURE 85. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +95°C

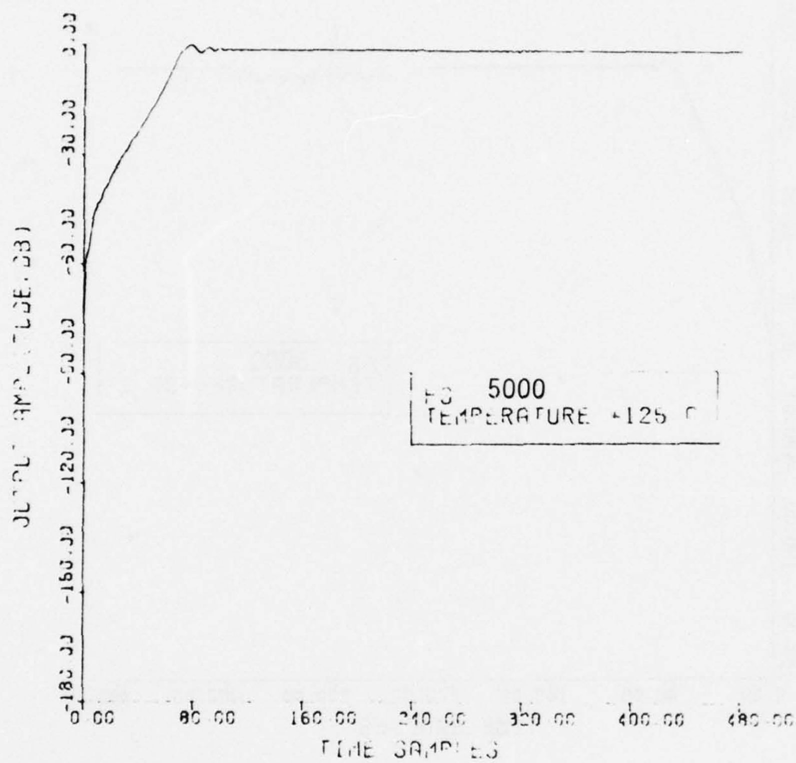


FIGURE 86. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND TEMPERATURE OF +125°C

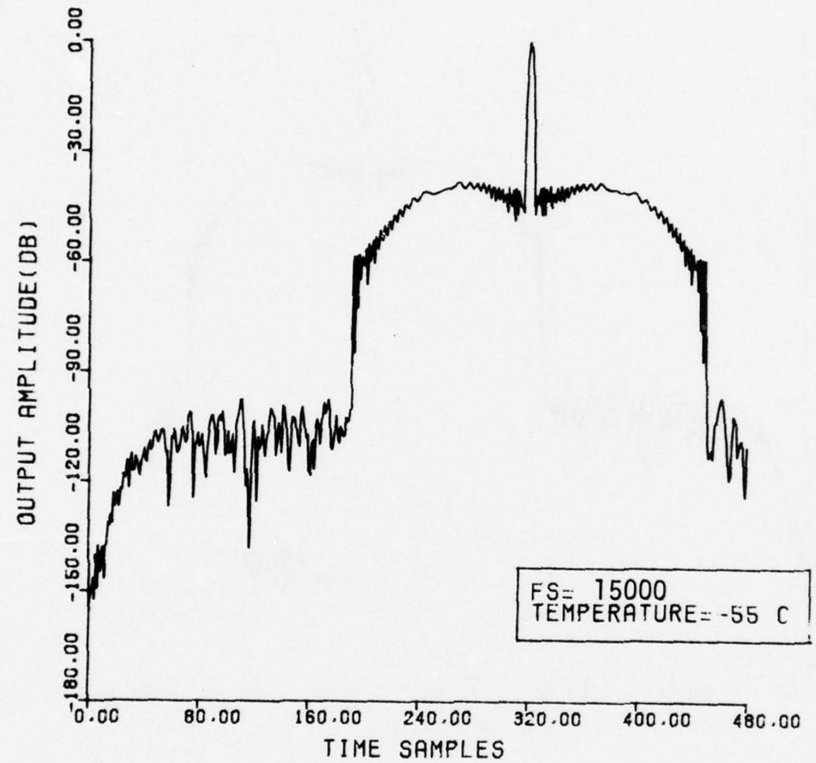


FIGURE 87. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF -55°C

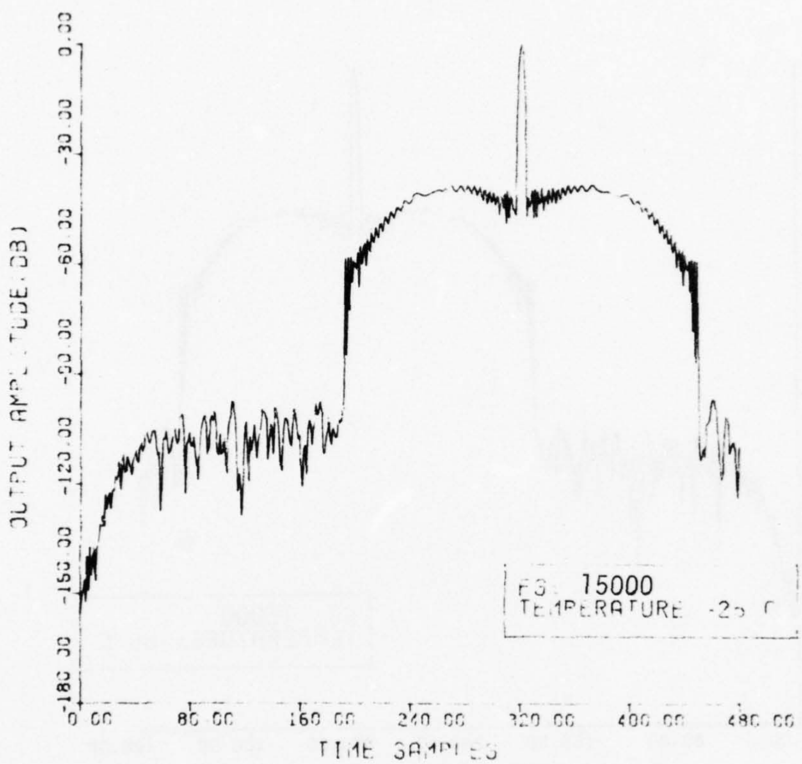


FIGURE 88. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF -25°C

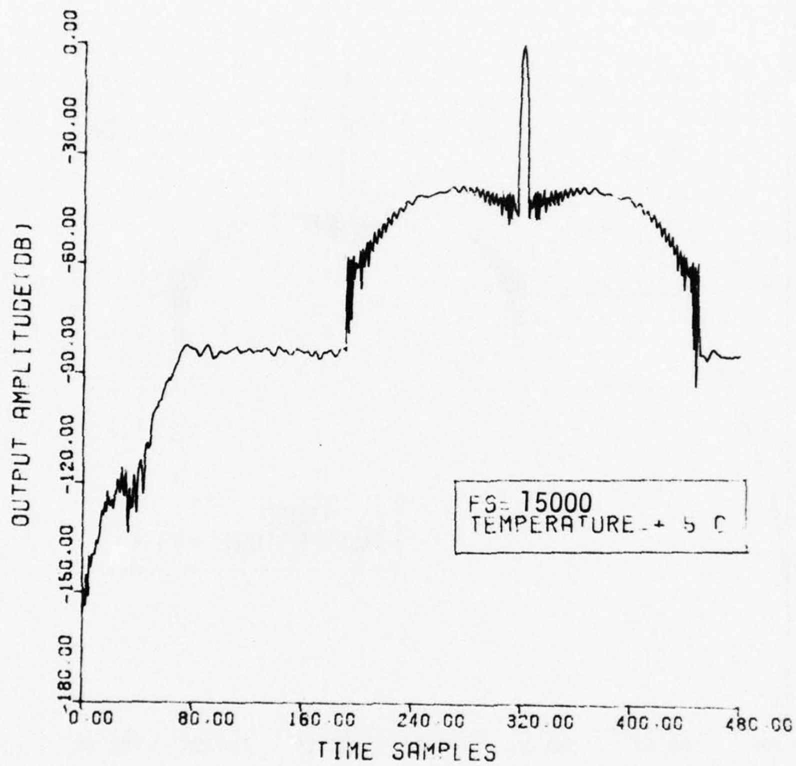


FIGURE 89. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +5°C

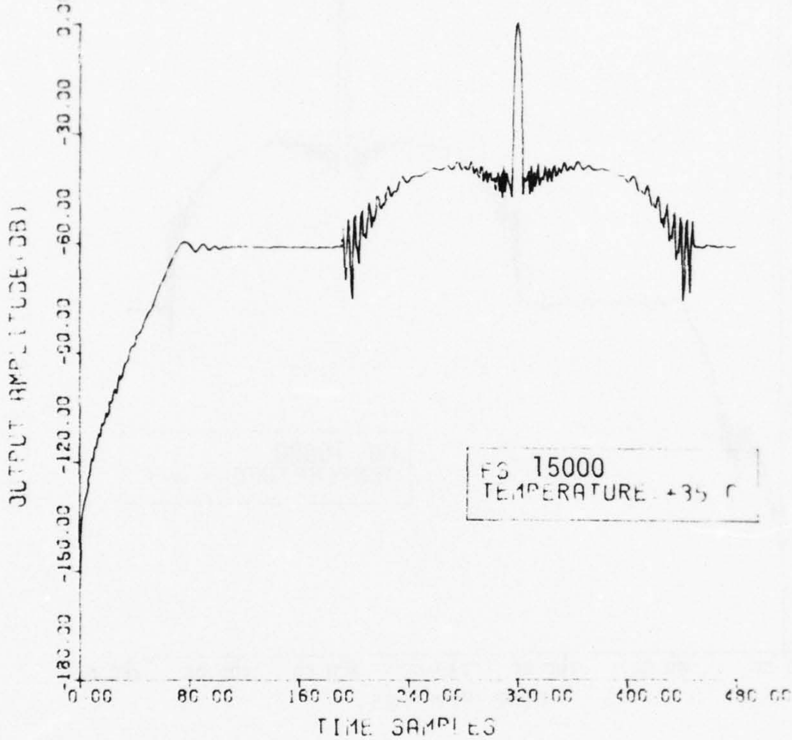


FIGURE 90. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +35°C

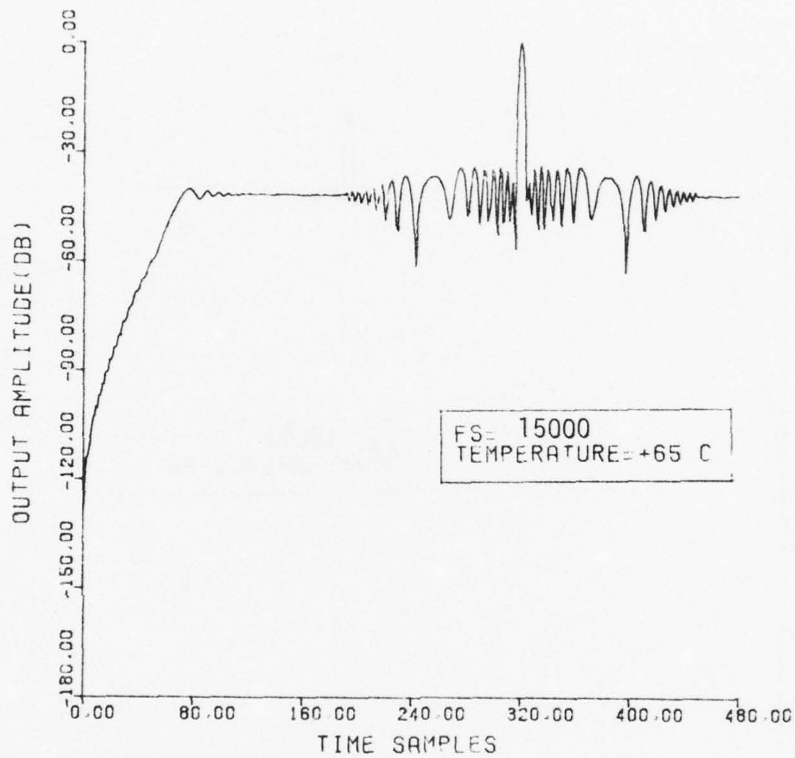


FIGURE 91. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +65°C

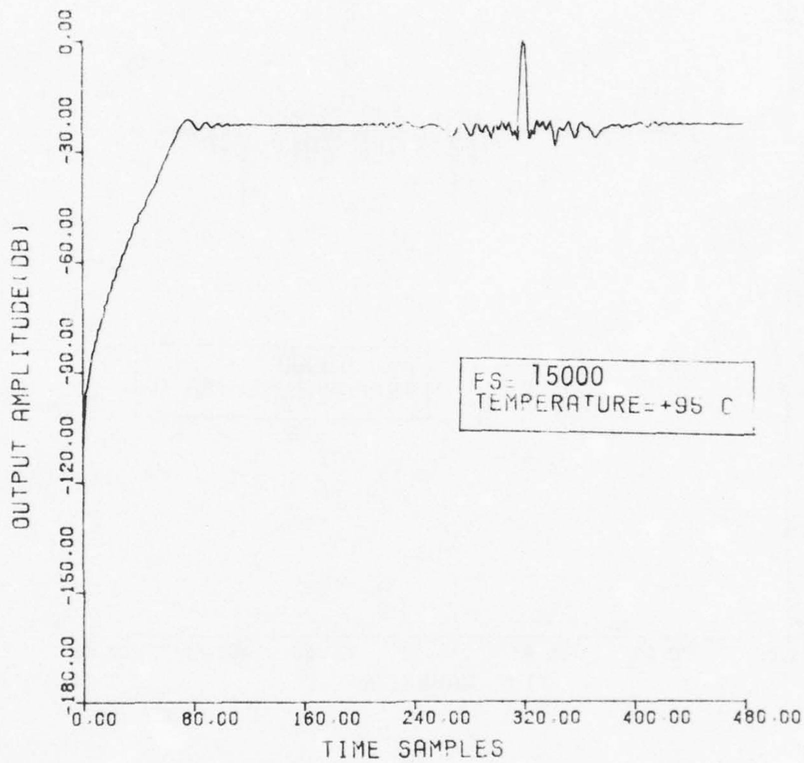


FIGURE 92. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +95°C

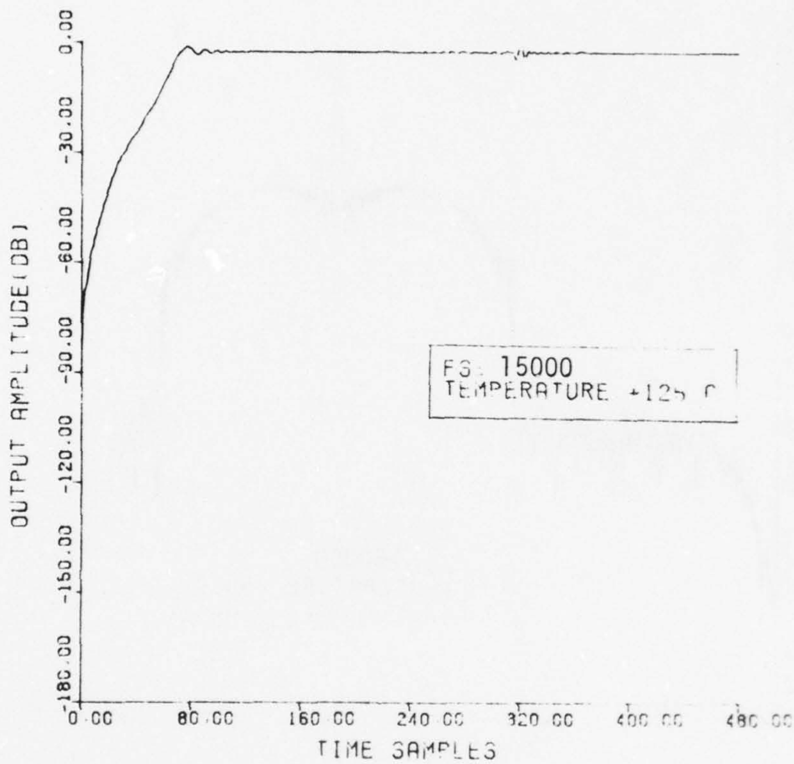
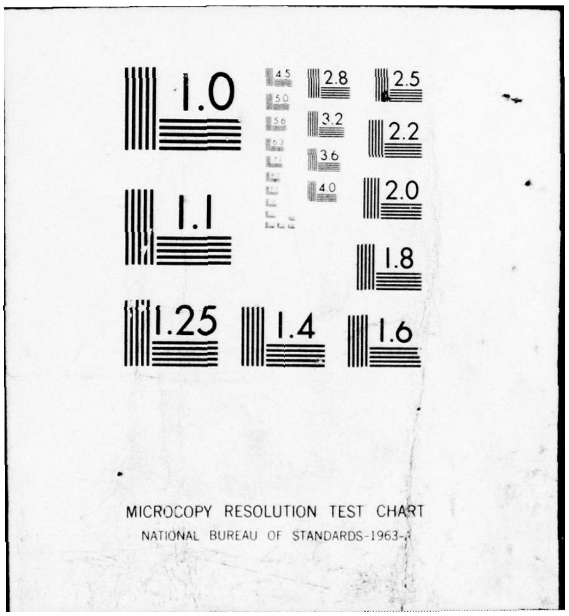


FIGURE 93. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 30,000 HERTZ AND TEMPERATURE OF +125°C

AD-A051 333 RCA GOVERNMENT SYSTEMS DIV MOORESTOWN N J MISSILE AND--ETC F/G 17/9
CCD SIGNAL PROCESSOR STUDY.(U)
DEC 77 L W MARTINSON, B P GAFFNEY, G J MAYER F30602-76-C-0280

UNCLASSIFIED RADC-TR-77-422 NL

3 OF 4
AD
A051 333


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

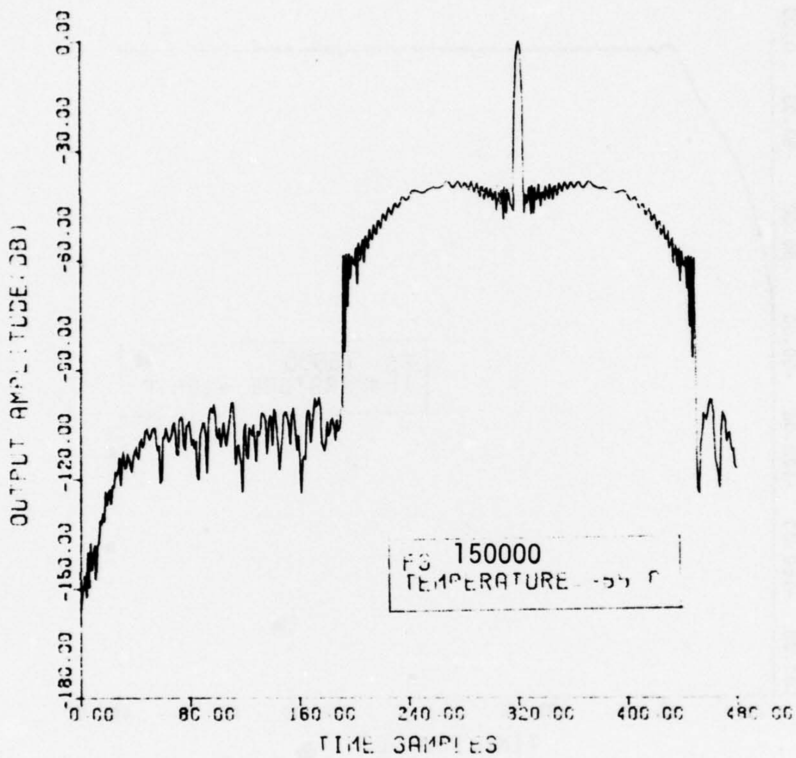


FIGURE 94. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF -55°C

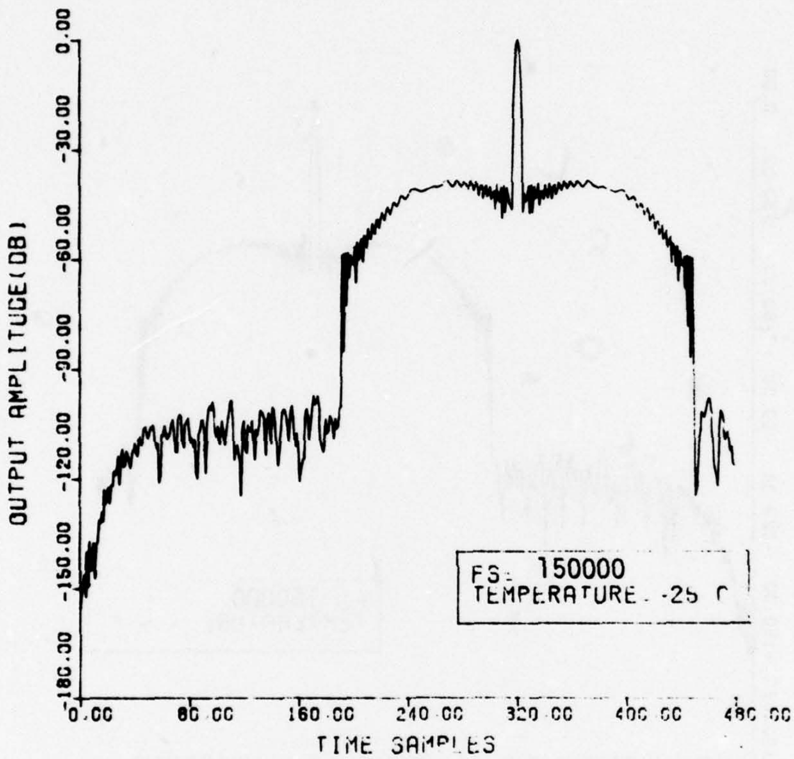


FIGURE 95. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF -25°C

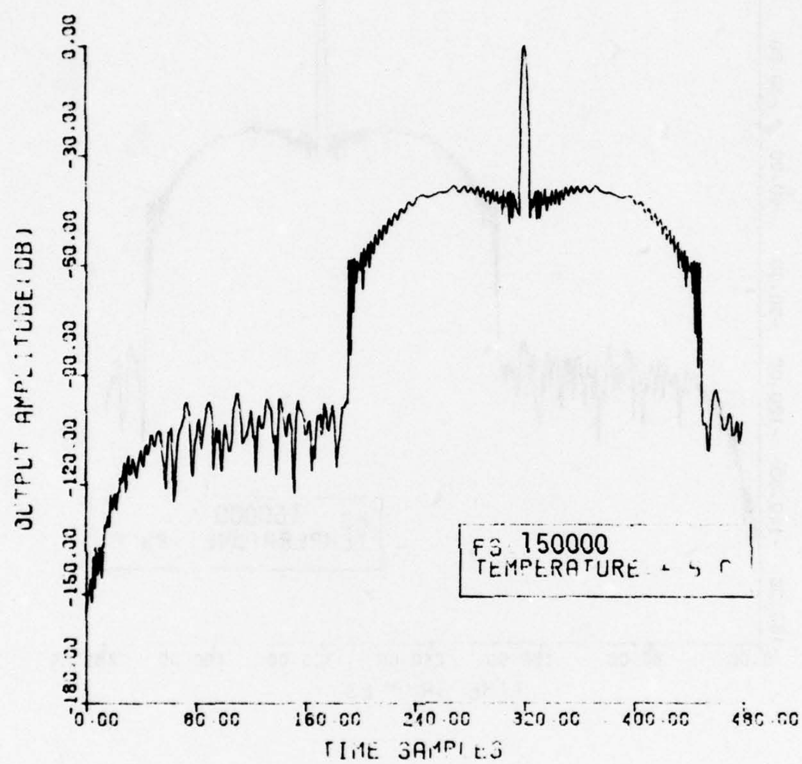


FIGURE 96. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +5°C

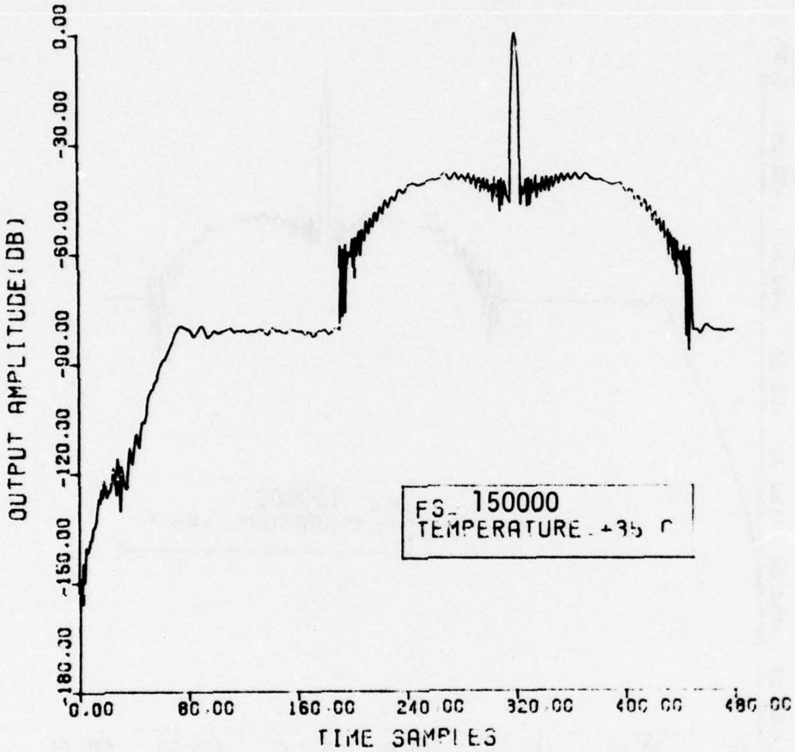


FIGURE 97. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +35°C

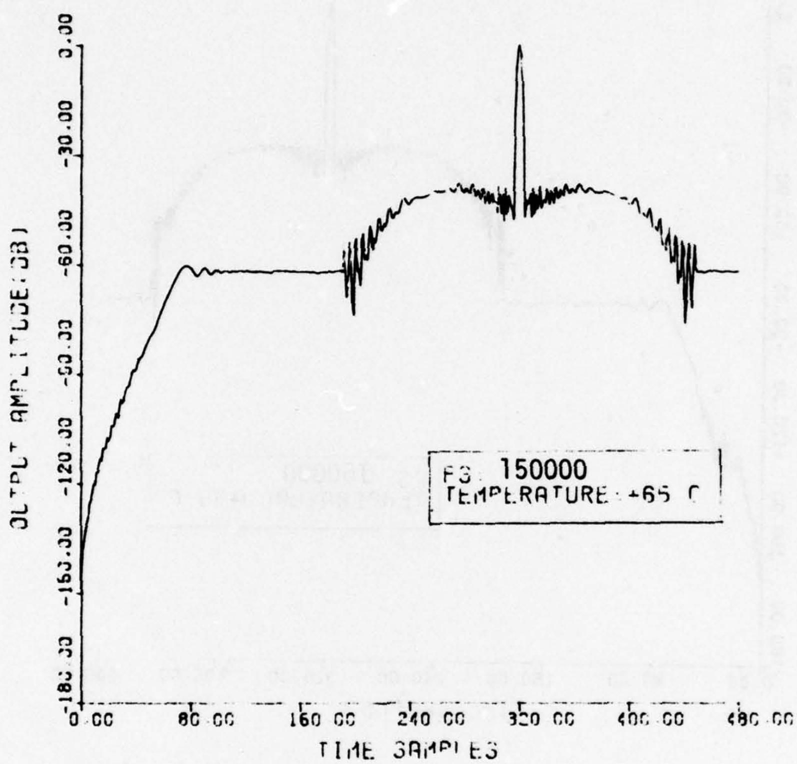


FIGURE 98. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +65°C

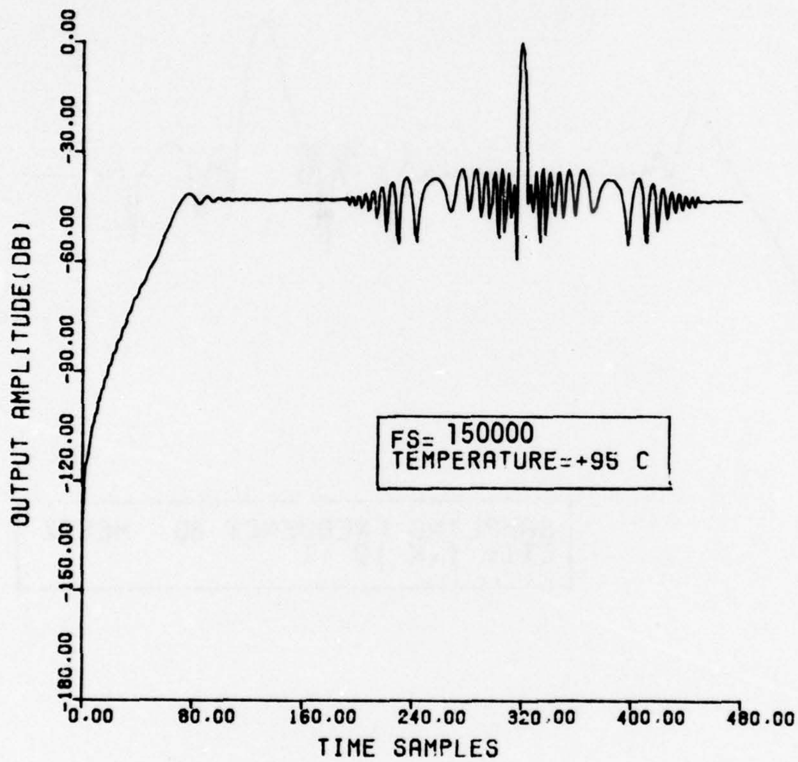


FIGURE 99. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 300,000 HERTZ AND TEMPERATURE OF +95°C

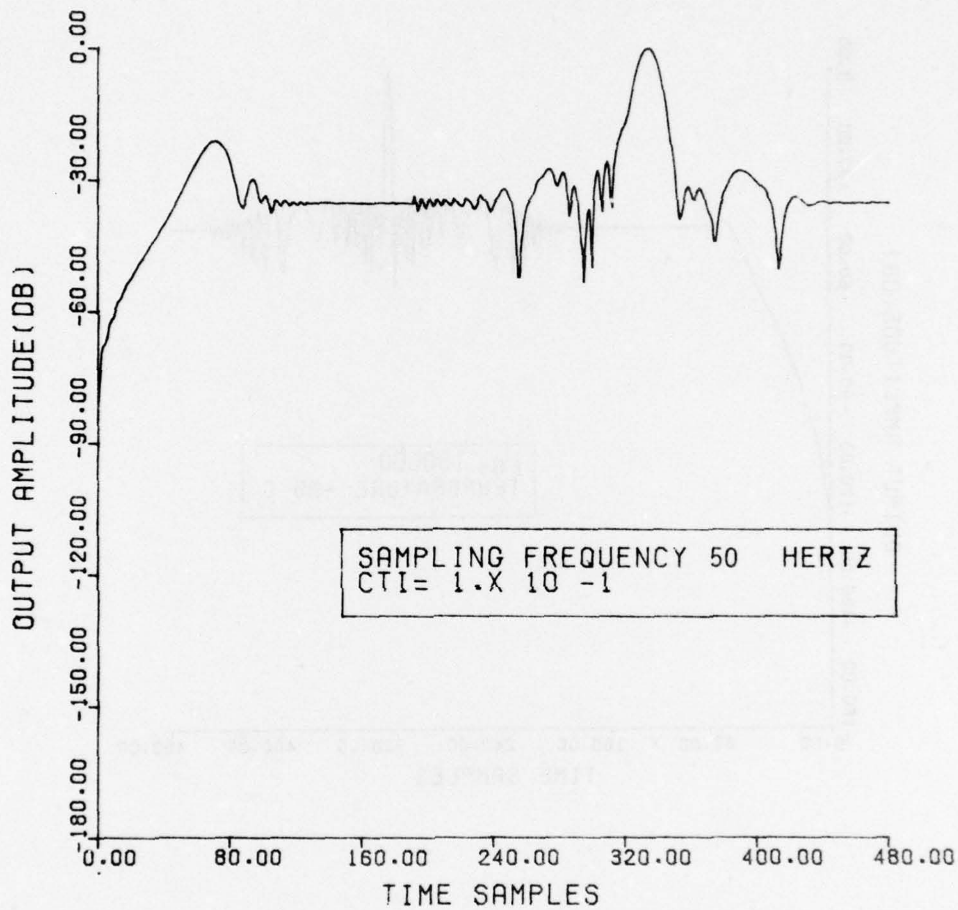


FIGURE 100. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND CTI = 0.1

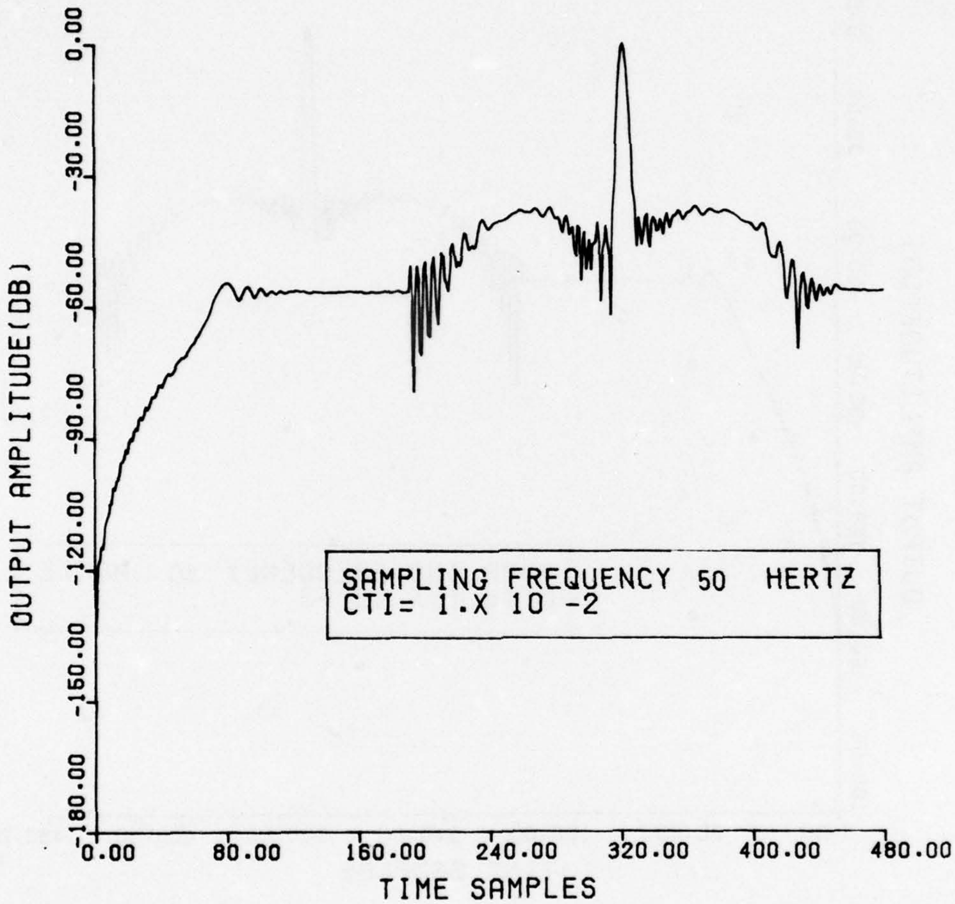


FIGURE 101. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND CTI = 0.01

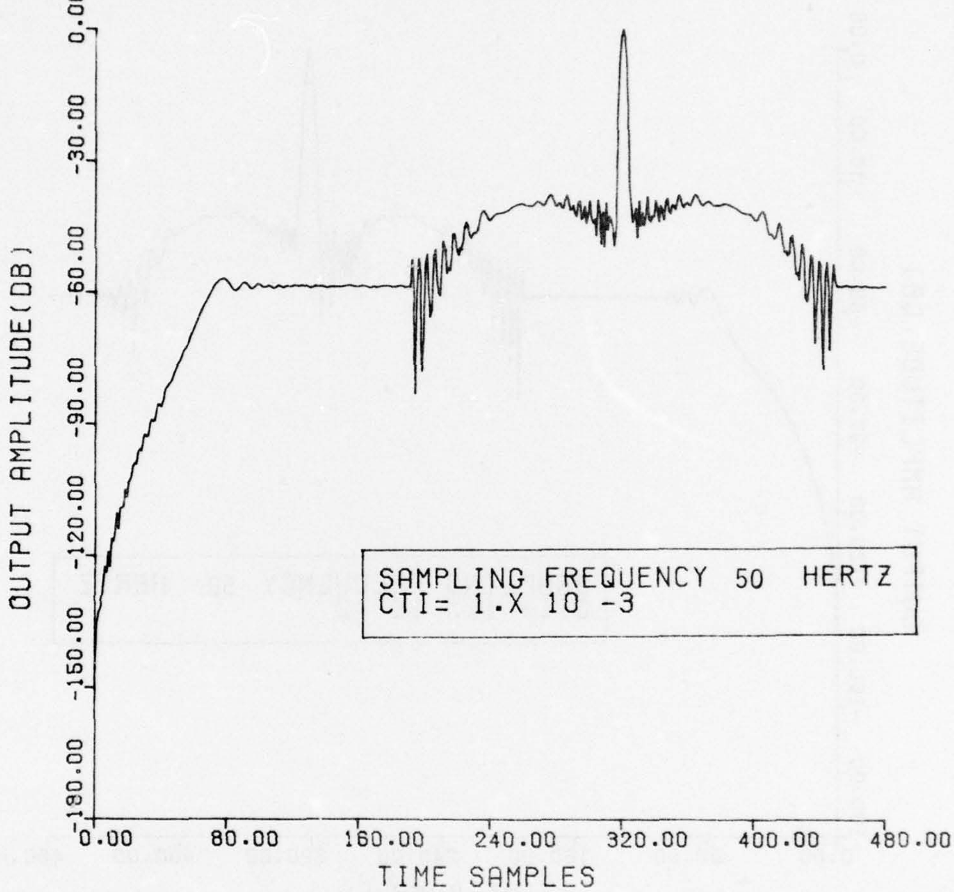


FIGURE 102. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 100 HERTZ AND CTI = 0.001

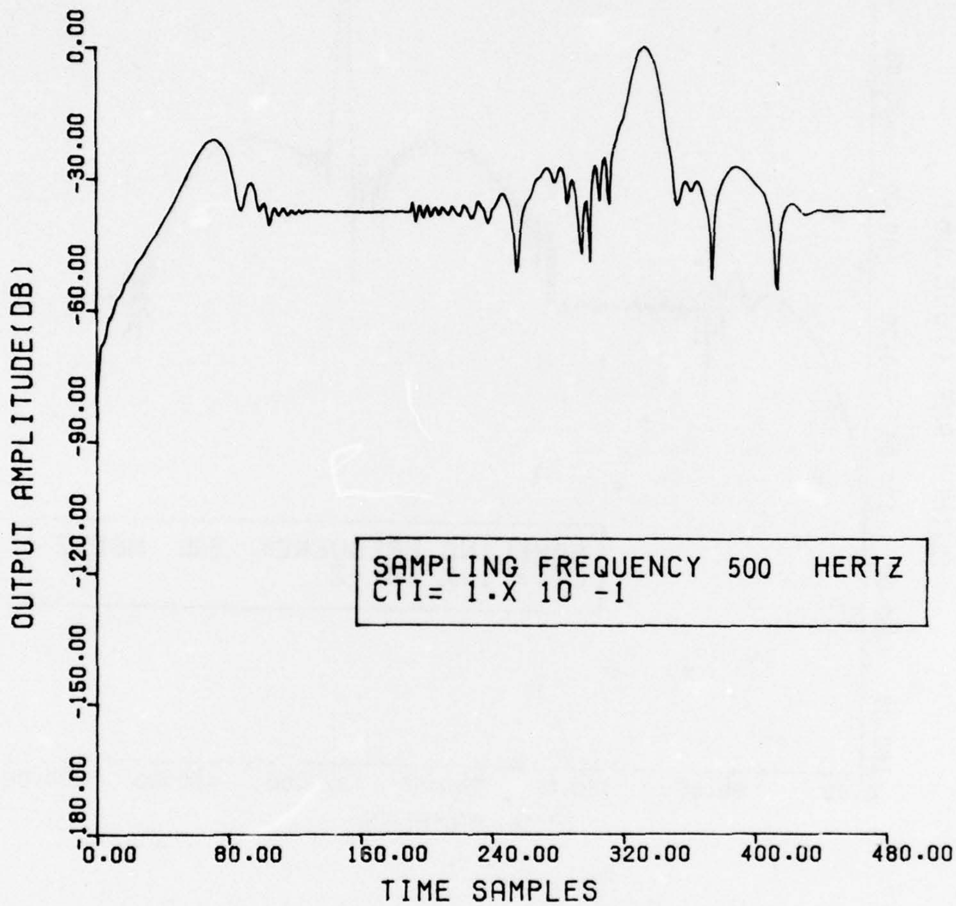


FIGURE 103. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 1,000 HERTZ AND CTI = 0.1

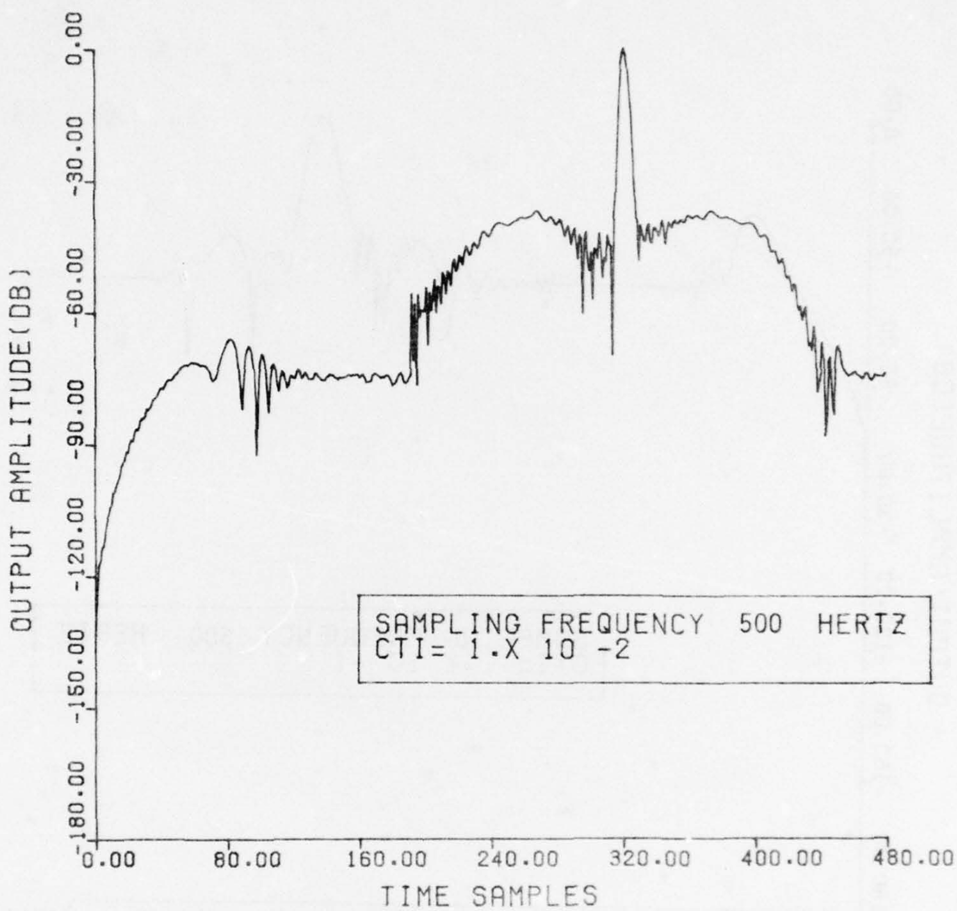


FIGURE 104. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 1,000 HERTZ AND CTI = 0.01

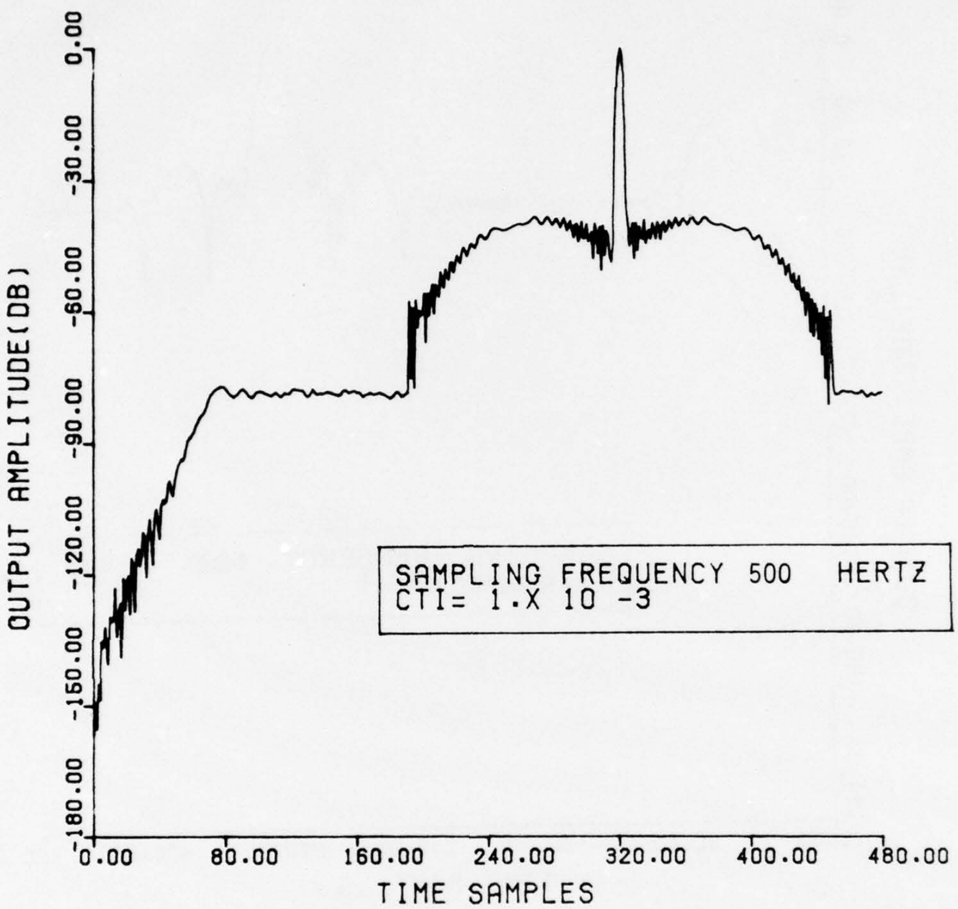


FIGURE 105. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 1,000 HERTZ AND CTI = 0.001

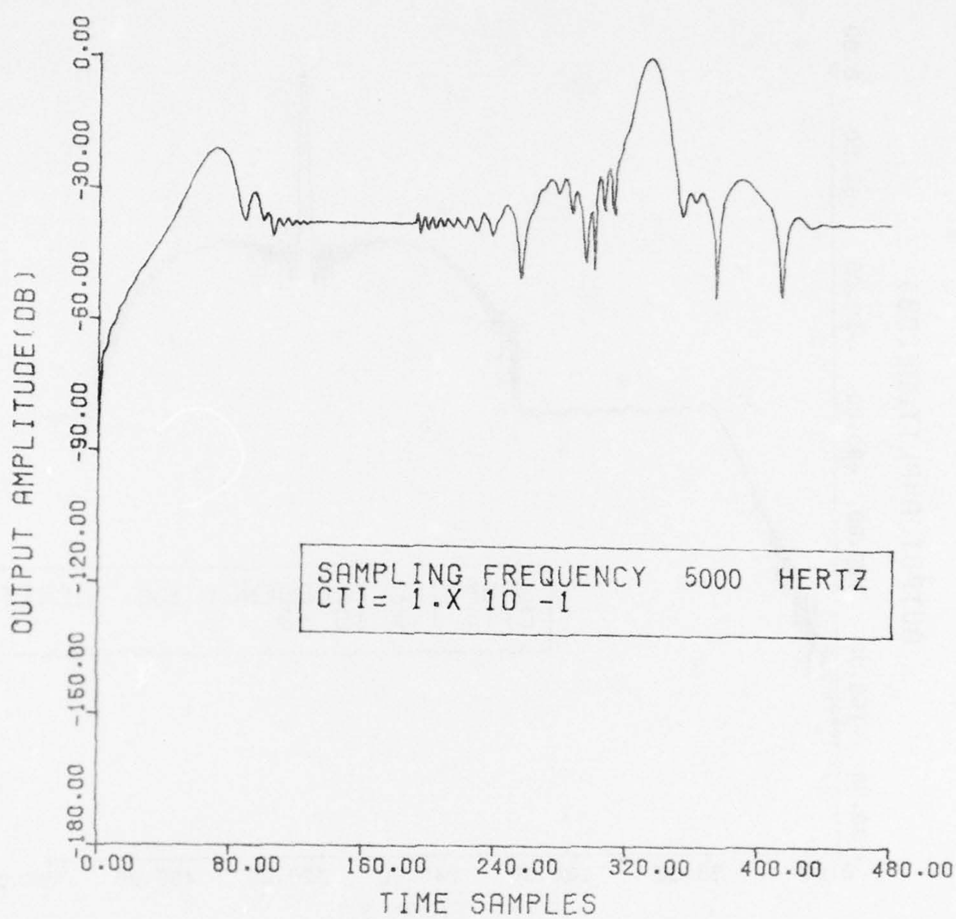


FIGURE 106. OUTPUT AMPLITUDE OF LINEAR MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.1

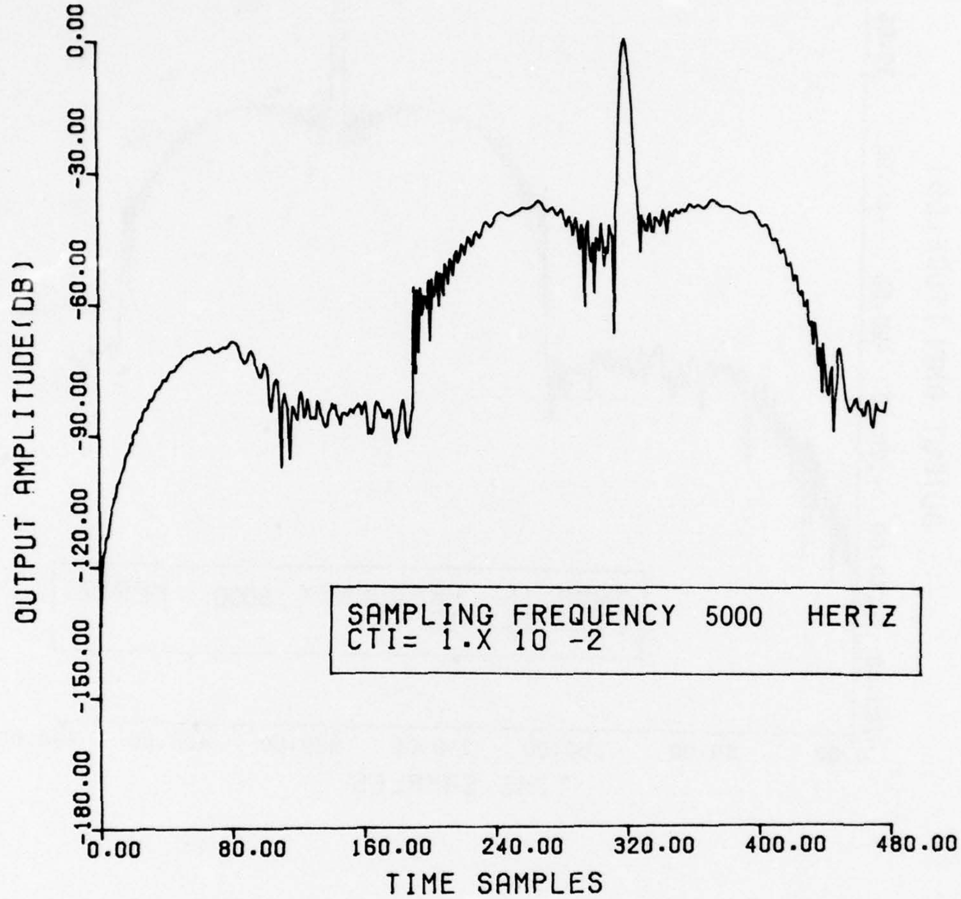


FIGURE 107. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.01

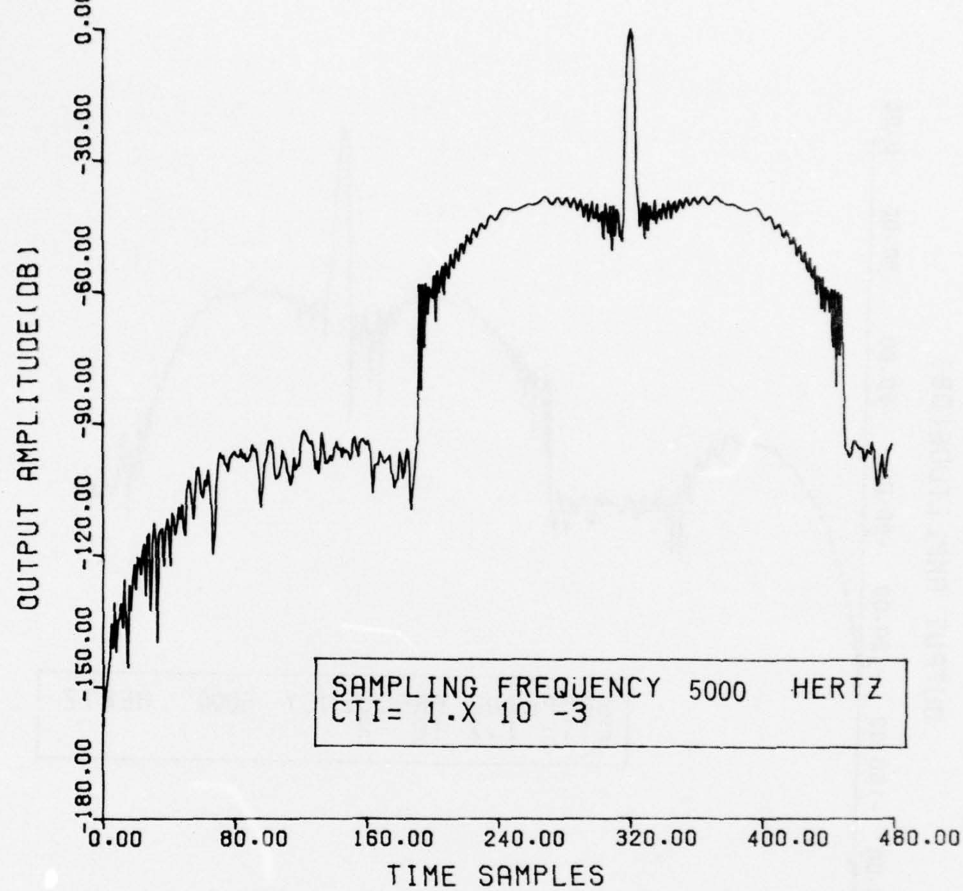


FIGURE 108. OUTPUT AMPLITUDE OF LINEAR FM MATCHED FILTER VERSUS TIME FOR CLOCK RATE OF 10,000 HERTZ AND CTI = 0.001

7.0 CCD COST/PERFORMANCE IMPLEMENTATION PROJECTIONS

7.1 PROGRAMMABILITY - ADAPTIVE, FLEXIBLE WAVEFORM PROCESSING

7.1.1 Objectives of Programmability

The desirability of programmability in radar signal processing functions stems from two basic desires. First for a given radar, the system operating parameters are generally developed analytically and their appropriateness to specific situations may be limited. The ability to change the waveform to match the radar task would provide the capability to use the basic radar resources of energy and bandwidth to their maximum efficiency in any given environment. This programmability will generally encompass variations in bandwidth, pulse length and waveform type. More elaborate programmability would involve changing the basic mode structure of the radar such as from pulse compression-MTI to a pulse-doppler mode with coherent MTD (moving target detection) processing.

A second objective of programmability is to provide interchangeability of signal processor units among different radar systems. While cost would be a factor here an even more important advantage would be performance upgrading. Programmable signal processing units could be tailored to any specific radar's requirements even though they were not originally designed for that application.

7.1.2 Programmability With CCD's

To achieve full programmability with CCD's it is necessary to have a reliable technique for switching and moving charge in opposing directions. While this would at first seem to be a straight-forward operation, consideration of a typical CCD structure will indicate the problems. Figure 109 shows a CCD delay line structure with the overlapping gates connected to clock busses. In order to contain charge within the limits defined by the gates and prevent clock bus coupling to the wells,charge barriers are introduced along the line. If it is desired to switch charge from moving down one line to another a means must be provided to tap the line through the barrier in a manner which transfers charge efficiently without crosstalk effects. As shown in Figure 109 this can be done by use of a transfer gate which serves as the barrier function when the gate is turned off. In the particular concept shown, charge can flow in either direction depending on the clock and control signal sequence. Thus the unit could also serve as a 2 to 1 multiplexer if the control busses are separated properly.

The fact that the charge moves through the substrate prevents one charge path from crossing another with both being operated simultaneously. This greatly restricts the complexity of functions. For example, one cannot easily construct a simple lattice network.

Table 35 lists a number of functions which can be considered for CCD processor programmability together with the means of achieving them and the general status of development.

Electrically variable tap weights are one of the most desirable features for

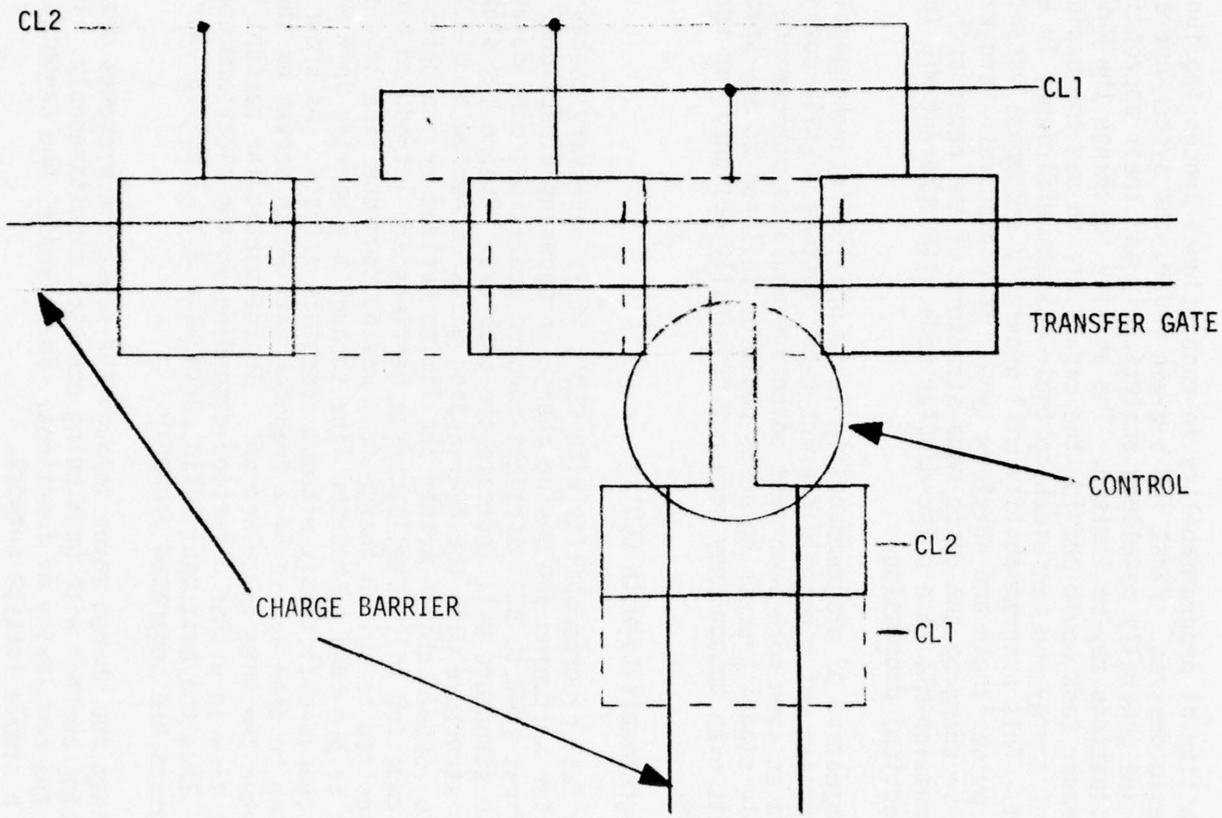


FIGURE 109. CONCEPTUAL CCD CHARGE TAP

TABLE 35. CCD PROGRAMMABILITY CONSIDERATIONS

TECHNIQUE CATEGORY	TECHNIQUES	TECHNOLOGY STATUS
Electrically Variable Weights	° Floating Gate Taps ° Integrated Multipliers ° Analog Storage	° Storage Time is Limited ° Multiplier is Problem ° Floating Gate Taps are Developed
Semi-Programmable Weights	(a) Split Gate Weighting (b) Electrically Programmed Permanent Weights	(a) Established But Not Truly Programmable (b) Technique Not Developed
Switching and Shifting Charge	Use of Transfer Gates and Barrier Controls	° Developed for Binary Signals ° Analog Technology Not Established
Variable Length	° Setting Weights to Zero ° Control Length by Switching	Requires Switching or Programmable Weights
Function Select	° Reconfiguration of Chip	Requires Extensive Development
Digital Logic Approach	Basic Digital Gate Functions Implemented with CCD Controls	° Maybe in Laboratory Stage ° Suitable for Pipelined Functions such as Digital Filters and FFT's

CCD transversal filters. The basic floating gate tap technique allows CCD delay registers to be non-destructively sensed. However, the multiplication of two signals stored on separate CCD registers with a multiplier integrated on the circuit has presented problems. The difficulty is in part due to the nature of the signals stored on the CCD. Each analog sample must have sample values about a bias level in order to retain a general bipolar form. In this case, each sample will have the form $x_i = b + x(t_i)$. A general filter function with the bias factors takes the form:

$$\int (b_1 + x(t))]b_2 + y(t-\tau)]\, d\tau$$

The foregoing integral will have four terms; the integral of the product of the two bias terms, the integral of each bias times the opposite signal and the integral of the product of the two signals. This is of course undesirable unless the spectrum of the signal products can be separated from the other terms. The CCD multiplier must, therefore, eliminate the bias cross products in the multiplication operation. Techniques for achieving this have been suggested [31, 32] which essentially cancel the bias terms of the two functions prior to or during multiplication. The techniques are, however, not well established with the latter reference [32] in 1975 describing a 32 tap filter with 32 multipliers whose output dynamic range was 20 dB, in part limited by external circuitry.

An electrically programmable filter by implication requires charge storage of a reasonable length of time. Dark current will limit this application just as it does general memory storage to storage times of 1 second or less unless the CCD is cooled.

A programmable feature which would greatly enhance the flexibility of CCD filters would be the ability to program fixed filter weights after fabrication in the manner of a PROM in digital memories. This would eliminate the costs of custom tailoring the weights for every CCD filter desired and would greatly reduce the cost of any particular CCD filter made in small to moderate quantities. This, however, is a need looking for an invention. No devices of this nature are known at this time.

The achievement of electrically variable lengths for CCD transversal filters and delay times will follow the development of programmable weights and methods of switching charge paths. Following along this same line would be the ability to change the signal processing function by reconfiguration of the CCD chip.

A final technique for programmability in CCD's should be mentioned and that is the implementation of digital logic devices with CCD's. Calculations [33] indicate that CCD's can provide a logic density improvement of a factor of 16 and attendent power improvement of 18 at a 5 MHz clock rate over I^2L technology. Applications are primarily suited for pipeline computation operations such as found with the FFT.

7.2 BANDWIDTH LIMITATIONS

The bandwidth capability or limitations of CCD signal processors fall into two categories; those due to the CCD device itself and those which involve

the peripheral circuitry required to operate the CCD.

7.2.1 CCD Bandwidth Limitations

Bandwidth handling capability of a CCD is essentially determined by the clock rate at which it can be operated. In considering wide-bandwidth application, concentration must necessarily be placed on buried channel, or peristaltic, CCD's since their charge transfer rates are much higher than surface channel CCD's.

A basic question is whether the inherent performance characteristics of CCD's will vary as a function clock rate. It has been shown in the simulation results reported in Section 6.0 that at low clock frequencies, performance is adversely affected because of dark current build-up. The maximum time that a signal can be held in a CCD prior to dark current build-up causing saturation effects is indicated in Table 36 . The low frequency limitation for delay line applications will not be a factor in most radar applications. This does not include application where long storage times are involved.

TABLE 36. LOW FREQUENCY LIMITATIONS OF CCD DELAY LINES
(DARK CURRENT FILTERING 20% OF WELL)

Temperature	Max Storage Time (Seconds)
- 55°C	>12 Seconds
- 25°C	>12 Seconds
+ 5°C	>12 Seconds
+ 35°C	6 Seconds
+ 65°C	0.75 Seconds
+ 95°C	< 0.1875 Seconds
+125°C	< 0.1875 Seconds

The CCD model developed for the simulation on this program has no noise or degradation sources which degrade the performance of a CCD as the clock rate is increased. Two recent studies [34 , 35] have been reported regarding the measured performance of CCD's at high clock rates. Chan, et al [34] conducted an interesting test on a 130 cell buried channel CCD. By initially loading the CCD at rates up to 105 MHz, holding the data, and reading it out at the lower rate of 100 kHz, the effects of higher frequency operation were examined. This fixed low output speed prevented degradations due to the output circuitry itself from being a factor. Linearity of the input structure was verified to give second and third harmonic distortion levels of about -54 dB. The transfer efficiency (>.999) was found to be constant over all operating frequencies and no other performance measures could be seen as a function of frequency other than that due to dark current build up at very low frequencies.

7.2.2 Clock, Control and Packaging Considerations

Although the CCD itself has not exhibited any important operating degradations up to the limitation imposed by charge mobility, the practical use of CCD's at high frequencies is a problem. The CCD has been developed in large measure by use of the circuit technology of digital logic. The analysis of CCD's follows the sampled data nature of digital signals. However, a CCD is a low-

noise analog device and optimum operation cannot be achieved unless very careful analog design and packaging procedures are followed. One rather obvious manifestation of the problem is apparent in the packaging of CCD's in dual-in-line packages. This packaging method, which was developed in conjunction with the growth of digital logic, is characterized by leads running closely parallel to each other over relatively large distances from the chip to package pins. The problems of cross coupling of clocks and signals in such a device are large. Recall that 100 MHz is a higher frequency than television channel 6 (84-88 MHz) and an appreciation of the shielding and lead lengths required in television tuners may give an insight into the packaging requirements for CCD's where 10 volt clocks are in close proximity to millivolt signals.

The design of clock drivers, output amplifiers and drivers are difficult problems and the high frequency performance of a CCD device will very likely fail due to efficiencies in these areas before CCD device limits are reached.

7.3 POST PROCESSING FUNCTIONS

The post processing functions in a radar signal processor generally refer to those following the basic matched filtering operation. Doppler processing is generally considered with the pulse compression system since it forms a matched filter for a target with a specific doppler. Post processing functions include: thresholding, range and angle estimation, bulk filtering, constant false alarm rate (CFAR) processing, interpolation, predictors and various pattern recognition procedures. Many of the functions are identified in Figure 2. The application of CCD's is possible in those cases where the computations can be pipelined. Implementation of many post processing functions with CCD's is even more dependent on achieving programmability and adaptability than the pre-post processor functions. An important consideration relative to the appropriateness of CCD processing is the processing rate requirements of specific functions and whether digital microprocessor based techniques will ultimately be the best approach.

7.3.1 Processing Rate Requirements

The question of potential competitive advantages for implementation of post processing functions with CCD's depends upon the computation rates and the functions required. Table 37 lists conventional post processing functions together with their relative computational rates and general architecture. Those in which a CCD-analog implementation is projected to perform at a lower cost than a microprocessor based digital system are indicated. In general, functions which are related to threshold detection such as interpolation and CFAR are candidates for CCD processing. Pattern recognition functions are CCD candidates because even though the duty factor is low relative to the pulse interval, the bandwidth will be high and computation rates similar to the thresholding functions are likely to be required.

7.3.2 Interpolation

Sampled data systems are characterized by non-optimum time sampling of the input data which causes a range straddling and an error in the estimate of the true target position. This effect is illustrated in Figure 110. The

TABLE 37. POST PROCESSOR CCD CANDIDATES

POST PROCESSING FUNCTION	COMPUTATION RATE	DUTY CYCLE	PRINCIPAL PROCESSING ELEMENTS (ARCHITECTURE)	REMARKS RE CCD IMPLEMENTATION	ADVANTAGE TO	
					CCD	MICRO-PROCESSOR
Threshold Detection	Video Sample Rate	100%	Amplitude Comparison	Peripheral CCD, Analog Circuitry	X	
Normal Threshold Computation	<< Sample Rate	~ 1%	Weighting & Adding Several Sensor Inputs	Requires Programmability		X
Interpolation	Sample Rate or Greater	100%	Transversal Filter	Programmability of Weights is Desirable	X	
CFAR	Sample Rate or Greater	100%	Transversal Filter	Programmable Weights for Adaptive CFAR	X	
Range & Angle Estimation	<< Sample Rate	< 1%	Add,Subtract,Mult., Divide,Small Delays	Specialized Analog Functional Would Do Mult. & Divide Operation		X
Pattern Recognition (Correlation, 2D Transform)	High	< 1%	Programmable Transversal Filter for 2D Transform	Computation Rates Are High Since Waveforms are Wideband	X	
Predictors, Coordinate Conversion, Kalman Filters	<< Sample Rate	Small	General Arithmetic Operations	Required Wide Programmability		X

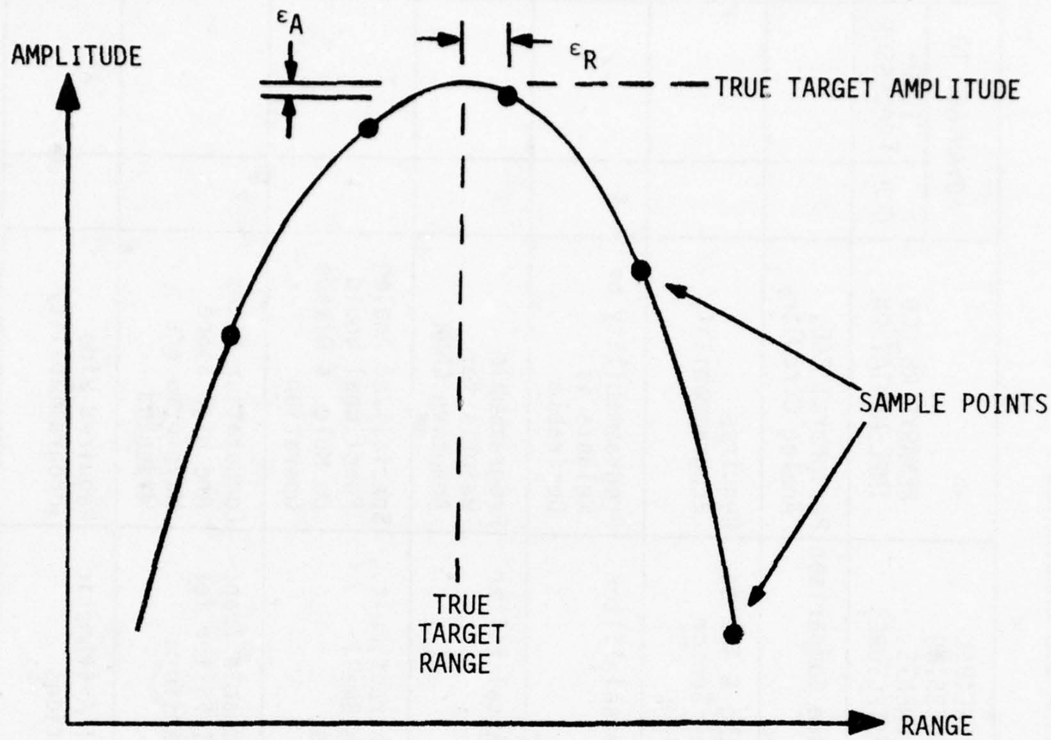


FIGURE 110. TARGET STRADDLING WITH SAMPLED DATA SYSTEM

problem can be avoided by sampling at a rate much higher than that required by the Nyquist sampling criteria. Figure 111 shows the straddling loss versus sampling rate.

Interpolation between samples which effectively increase the sampling rate can be achieved by a number of filter approaches. An optimum filter can be derived which is closely matched to the spectrum of the compressed pulse. A typical configuration is the 4-point polynomial interpolator shown in Figure 112. This is virtually a standard transversal filter and it can be readily implemented with CCD's. One filter is necessary for each inter-sample interpolated point.

7.3.3 CFAR Processing

The objective of a constant false-alarm rate (CFAR) process is to adaptively adjust the target detection threshold to the environment. A situation is depicted in Figure 113 where a large clutter return is present. If a fixed threshold were used, it would have to be set above the clutter return. However, if the threshold is made to adapt to the clutter return, the small target outside the clutter return can be detected. An implementation of a CFAR system designed to accomplish the required adaptivity is shown in Figure 114. In this case, the sidelobe levels of the compressed pulse output are measured in the

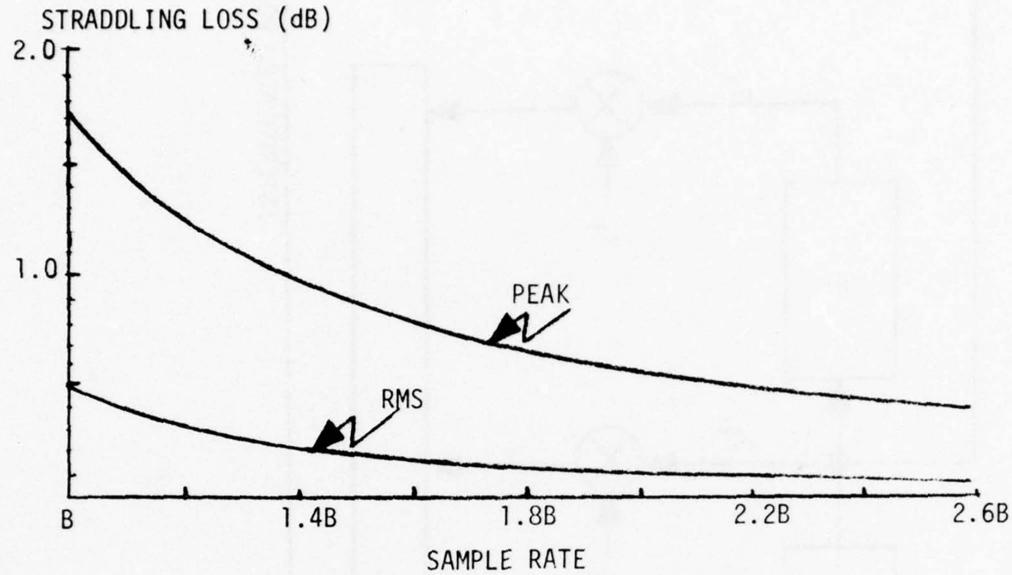


FIGURE 111. STRADDLING LOSS VERSUS SAMPLING RATE FOR HAMMING WEIGHTED COMPRESSED LINEAR FM PULSE OF BANDWIDTH, B

vicinity of the range sample of interest and these levels are used to adjust the threshold level. This entire function can be implemented with CCD's.

7.4 PRACTICAL CCD IMPLEMENTATIONS

7.4.1 Peripheral CCD Circuitry

A principal feature of CCD's is their small size and power dissipation in relation to their functional capability. However, in ascertaining the total cost of a CCD system, the peripheral circuitry necessary to operate the devices must be included. This aspect of CCD's is perhaps the most critical problem, or deterrent, to more widespread application. The operation of CCD's involve multiple phase, multiple level clock signals, bias levels for the input gates, output amplifiers, and finally the cancellation or filtering of the clock signal from the output. The amount of control circuitry required will vary among the CCD devices and with the sophistication of the designer, but an example will illustrate the situation. A commercially available CCD, a dual 455 stage (1H) delay line,is marketed by Fairchild. This unit, designated the CCD 321,is offered with a design development module containing all required control signals. The component count of the module (type CCD 32M) includes:

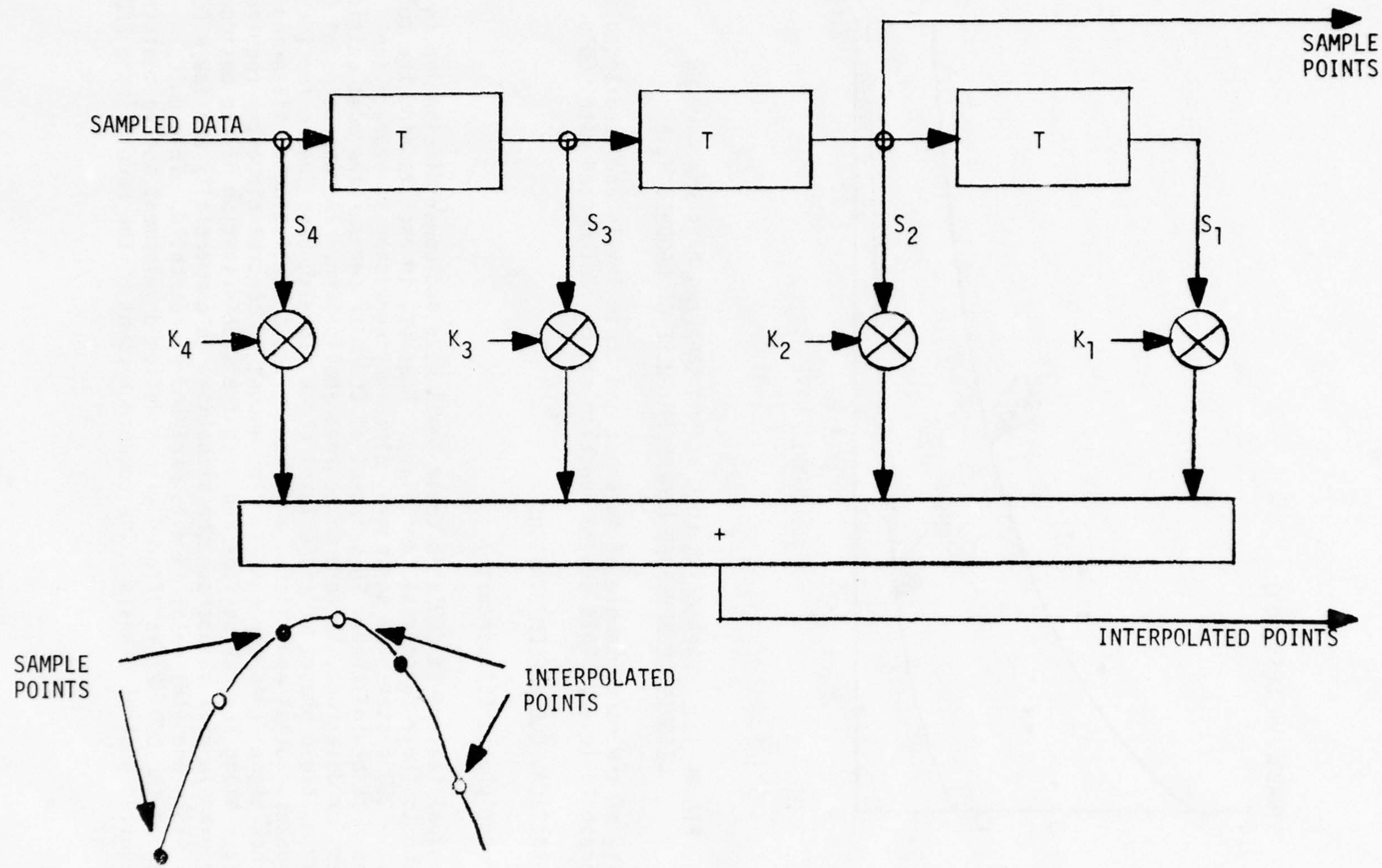


FIGURE 112. 4-POINT POLYNOMIAL INTERPOLATOR

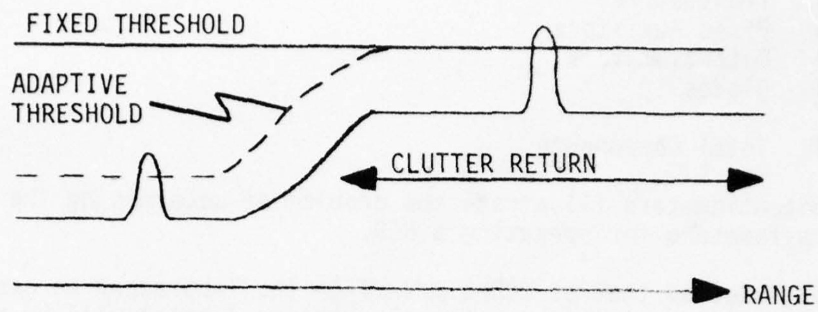


FIGURE 113. VARIABLE THRESHOLD ENVIRONMENT

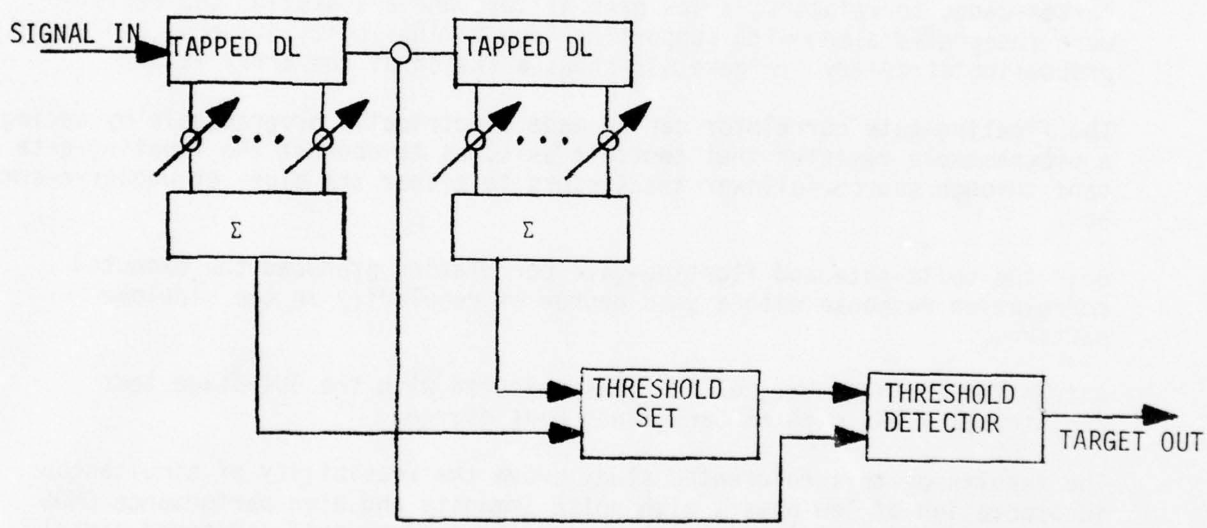


FIGURE 114. TYPICAL CFAR IMPLEMENTATION

9	Integrated Circuits
44	Capacitors
14	Transistors
39	Fixed Resistors
10	Potentiometers
23	Diodes
139	Total Components

The 10 potentiometers illustrate the problem of determining the optimum control parameters for operating a CCD.

It can be expected that as CCD's move from the laboratory to systems, the needs relative to precise operational characterization will be met. The other development which can be expected to improve the hardware implementation of CCD's will be the integration of control signals on the CCD chip.

7.4.2 On-Chip CCD Controls

The integration of CCD control signals on the CCD circuit is a target of CCD development effort at this time. The most extensive program of this reported thus far appears to be a program of RCA for the US Army Electronics Command [36]. A complex CCD array comprised of split-gate and floating-gate 13-bit Barker-coded correlators, a low pass filter, and a 504-stage CCD register were integrated along with supporting CMOS timing/logic, drivers, and signal processing circuitry. Figure 115 shows a sketch of the array layout.

The floating-gate correlator can be made electrically programmable by adding a programmable register that controls switches to connect the floating-gate taps through source follower transistors to either the plus- or negative-sum bus.

Both the split-gate and floating-gate correlators produced the expected correlation response with a good degree of regularity in the sidelobe patterns.

A transfer inefficiency of 10^{-5} was measured with the 504-stage test register at 1 MHz with no background bias charge.

The results on this referenced study prove the feasibility of simultaneous incorporation of low power, high noise immunity and high performance CMOS on-chip with high efficiency CCD devices to achieve self-contained signal processing components such as analog delay and transversal filters which do not require complex external support circuitry.

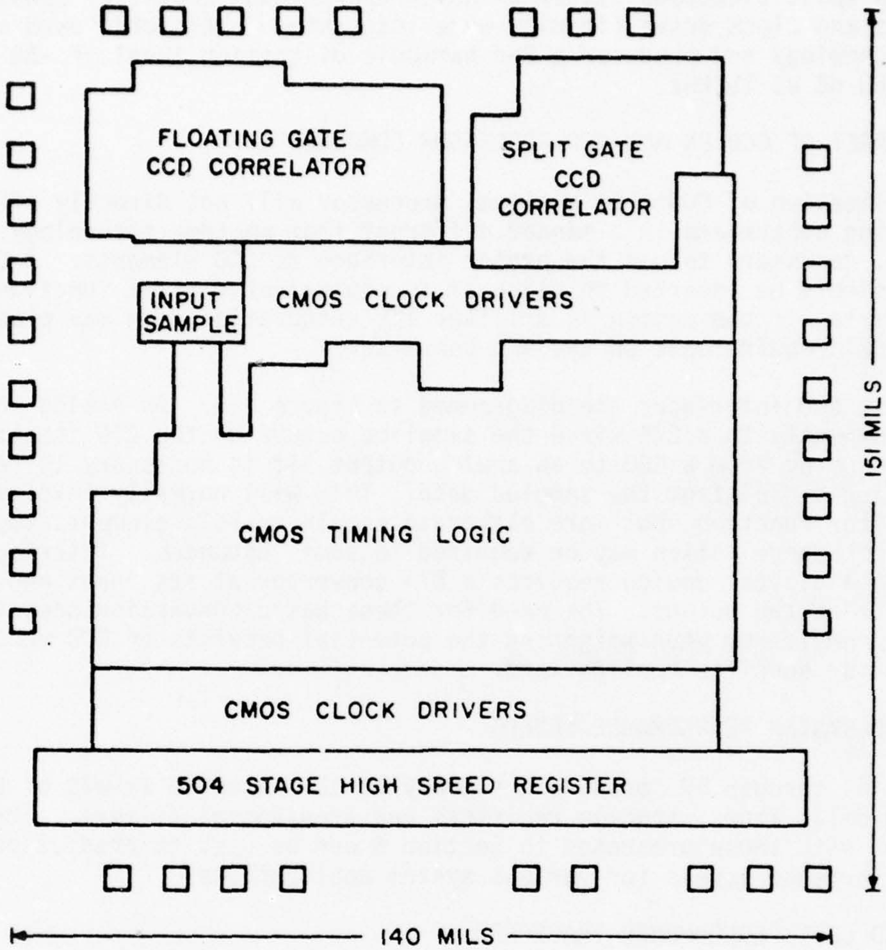


FIGURE 115. LAYOUT OF CMOS/CCD TEST CHIP

A recent paper [37] by researchers at Bell Labs discussed the development of a 55 tap split electrode filter on which operational amplifier sensing circuits and clock drive circuits were integrated. This chip used silicon NMOS technology and produced a 2nd harmonic distortion level of -50 dB and a S/N of 60 dB at 15 kHz.

7.5 IMPACT OF CCD ON NON-CCD PROCESSOR COMPONENTS

The application of CCD's in a signal processor will not directly affect other processing subsystems in a manner different from another technology. It is, however, necessary to use the proper interface to CCD elements. A CCD unit cannot simply be inserted in place of an equivalent digital function since, for example, if the device is a filter its integration gain may place additional requirements on the A/D converter.

The basic CCD interfaces are diagrammed in Figure 116. An analog input can be fed directly to a CCD since the sampling occurs on the CCD itself. However, in going from a CCD to an analog output, it is necessary to recover the analog signal from the sampled data. This will normally involve a low pass filter function, but more elaborate sample-on-hold elements together with clock cancellation may be required in some instances. Interfacing a CCD with a digital device requires a D/A converter at its input and an A/D converter at the output. The need for these basic conversion operations must be considered when weighting the potential benefits of CCD versus digital for specific applications.

7.6 SUB-SYSTEM PERFORMANCE LEVELS

Tables 38 through 40 provide a summary of the expected levels of performance for CCD delay lines, storage registers and transversal filters. These charts together with those presented in Section 6 can be used to predict potential CCD performance levels for various system applications.

7.7 CCD COST/PERFORMANCE TRADEOFFS

General projections on CCD system costs relative to other technologies can be made, but specific tradeoffs will depend on the application and the competing technology. For low data rate applications, microprocessor techniques will prevail as most cost-effective. As the data rates and processing requirements increase to the hundreds of kilohertz up to 10 MHz, CCD's will find increasing application. Buried channel CCD's operate up to and beyond 100 MHz. Figure 117 indicates general speed performance categories for various technologies. The line of demarcation between different approaches will fluctuate depending on the specific application. Note that every category of processor can be built with special purpose digital hardware. This involves paralleling at the very high rates.

Costs can be expected to follow the basic pattern of Figure 118. A standard implementation using MSI digital technology will be relatively low in cost but as the number of units to be constructed increases, the parts cost will become dominant. Thus initial investments in either LSI or CCD development will produce substantial savings in the end. Since fewer chip designs are required for CCD's and fewer parts will be required in the system, the CCD

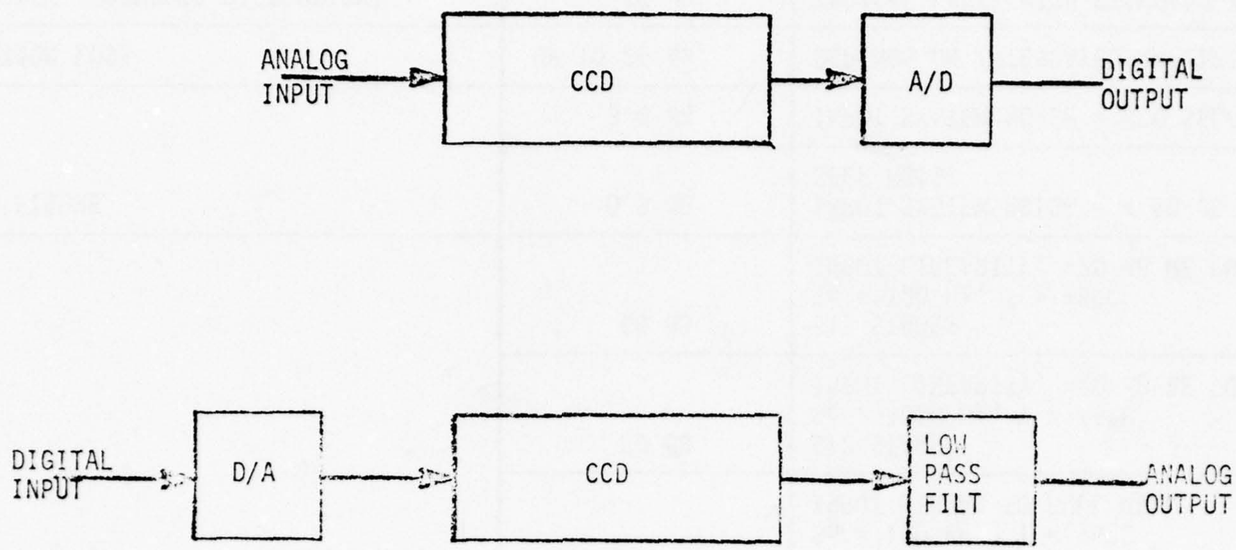


FIGURE 116. CCD - ANALOG - DIGITAL INTERFACE

TABLE 38 . EXPECTED CCD DELAY LINE PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE	115 dB	512 STAGES S_R = 100 kHz, T = +5°C INPUT LINEAR TO FULL WELL
	80 dB	512 STAGES S_R = 1000 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
	60 dB	512 STAGES S_R = 100 Hz, T = +5°C INPUT LINEARITY, -20 dB RE FULL WELL
NOISE FIGURE	0.3 dB	INPUT SYSTEM NOISE = + 10 dB RE TO CCD SELF NOISE
	3.0 dB	INPUT SYSTEM NOISE = CCD SELF NOISE
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INTEGRATED AMPLIFIERS
LINEARITY (HARMONIC DISTORTION)	-45 dB	TYPICAL LEVEL WITH STANDARD INPUT TECHNIQUE (MEASURED RESULTS)

TABLE 39. EXPECTED CCD STORAGE REGISTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC	MEASURE	CONDITIONS
DYNAMIC RANGE*	52 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, RE FULL WELL
	24 dB	STORAGE TIME = 12 SEC TEMPERATURE = 35°C, RE FULL WELL
	73 dB	STORAGE TIME = 1 SEC TEMPERATURE = 5°C, RE FULL WELL
	32 dB	STORAGE TIME = 12 SEC TEMPERATURE = 5°C, -20 dB RE FULL WELL
NOISE FIGURE INSERTION LOSS LINEARITY	SAME AS DELAY LINE CASE	

* THE DYNAMIC RANGE FOR CCD'S IN A STORAGE MODE IS LOW BECAUSE OF THE BUILD-UP OF DARK CURRENT VARIATIONS WHICH ARE AVERAGED OUT IN THE DELAY LINE CASE.

TABLE 40. EXPECTED CCD TRANSVERSAL FILTER PERFORMANCE BASED ON MEASUREMENTS, LITERATURE AND SIMULATION

CHARACTERISTIC*	MEASURE	CONDITIONS	
MAX SIDELOBE LEVEL (IDEAL = -39.6, TW PRODUCT = 65)	-39.5 dB	TAP ERRORS = 1%	T = 5°C CLOCK RATE (f_s) = 10^5 Hz
	-39.3 dB	TAP ERRORS = 3%	
	-35.6 dB	TAP ERRORS = 10%	
	-36 dB	f_s = 10 kHz TEMP. = 95°C	ZERO TAP WEIGHT ERRORS
	-38.5 dB	f_s = 10 kHz TEMP. = 65°C	
DYNAMIC RANGE (OUTPUT) CCD FILTER = 129 STAGES, TW = 65	80 dB	f_s = 100 Hz TEMP. = -25°C	RE FULL WELL
	60 dB	f_s = 100 Hz TEMP. = 5°C	
	60 dB	f_s = 300,000 Hz TEMP. = 65°C	
	110 dB	f_s = 3000 Hz TEMP. = -25°C	
NOISE FIGURE	0.3 dB	INPUT SYSTEM NOISE = +10 dB RE TO CCD SELF NOISE	
	3.0 dB	INPUT SYSTEM NOISE = CCD SELF NOISE	
INSERTION LOSS	UP TO 26 dB	DEPENDS ON INTEGRATED AMPLIFIERS	
LINEARITY (HARMONIC DISTORTION) CCD FILTER = 129 STAGES, TW = 65	-63 dB	RE OUTPUT	
	-45 dB	RE INPUT	

* THESE MEASUREMENTS APPLY TO CORRELATORS, CONVOLVERS, MATCHED FILTERS AND CZT SPECTRUM ANALYZERS IN SO FAR AS FUNDAMENTAL CCD IMPOSED LIMITATIONS.

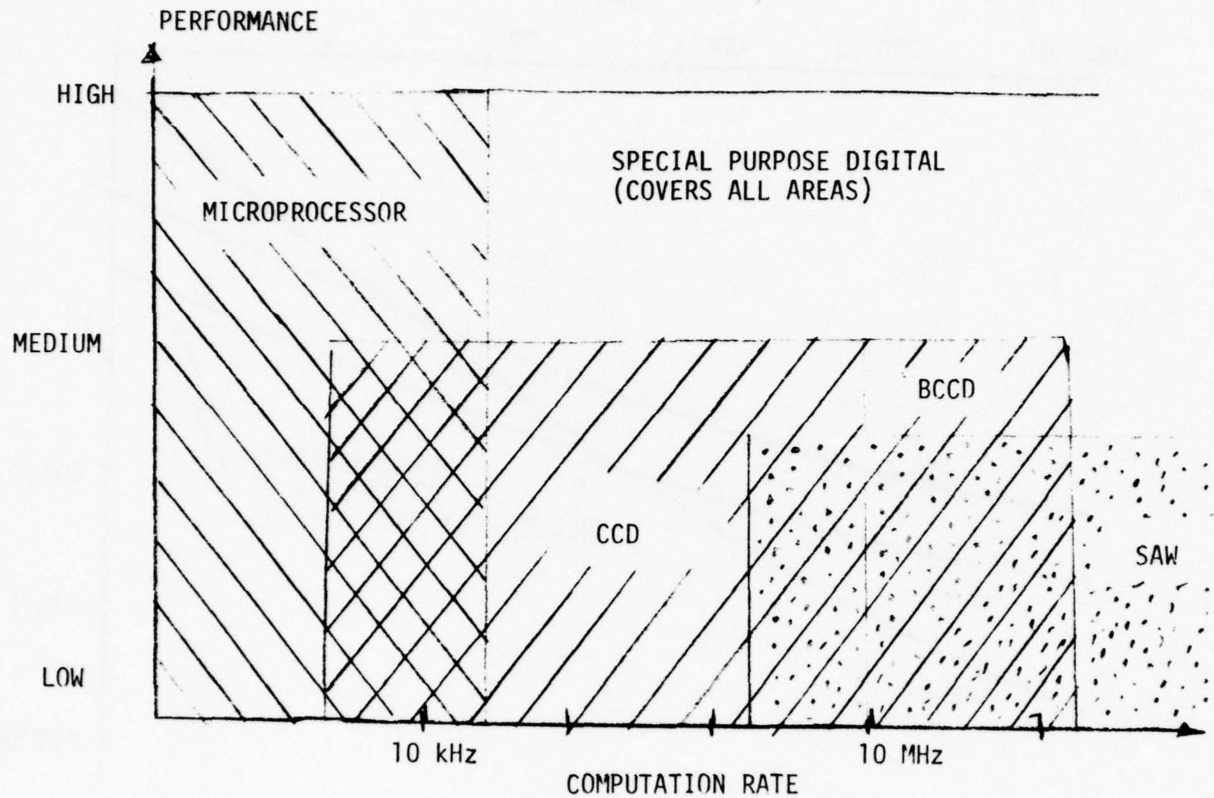


FIGURE 117. TECHNOLOGY CATEGORIES

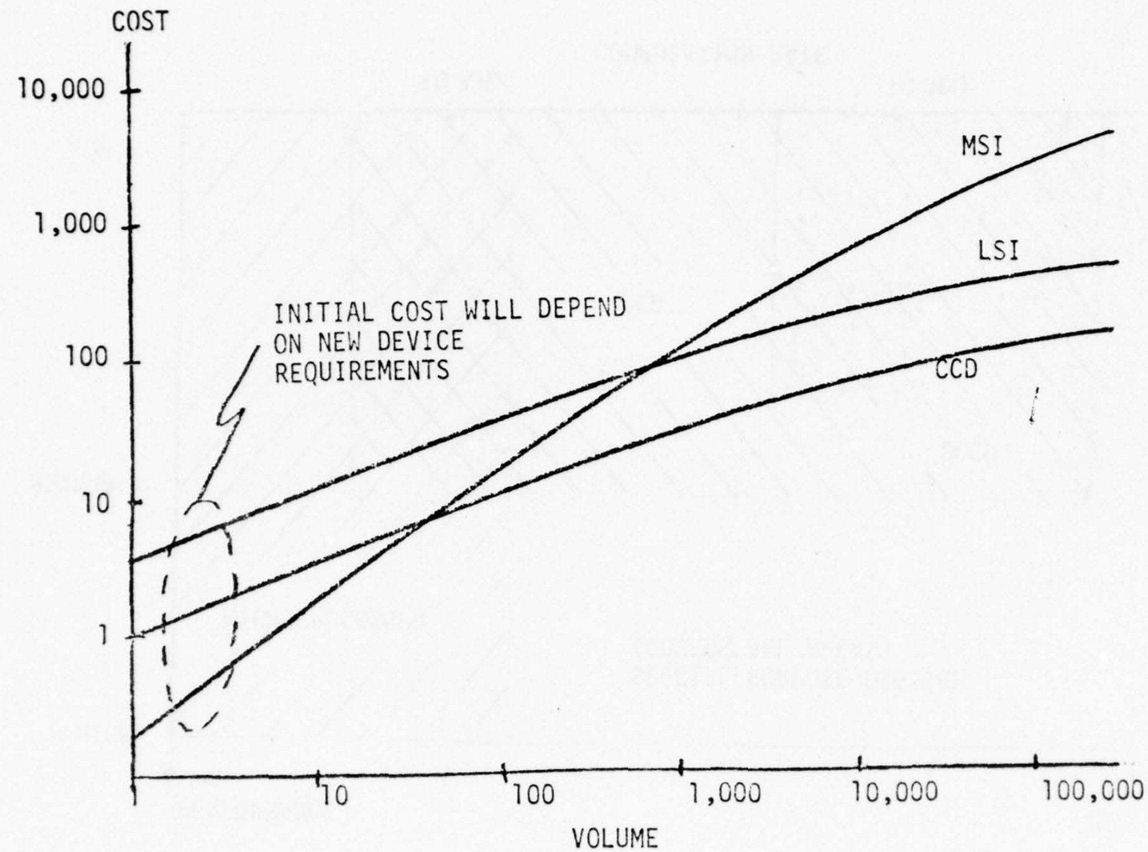


FIGURE 118. TECHNOLOGY COST TRENDS

unit costs will be lowest for large volumes. The crossovers of "break-even" costs indicated in Figure 118 can not be assumed to hold in general. Each application will produce a different tradeoff.

REFERENCES

1. Lerch, Charles S. Jr., "Satellite Surveillance Radar", Chapter 32 of Radar Handbook, M. I. Skolnik editor, McGraw-Hill, 1970.

2. F.L.J. Sangster, "MOS Integrated Bucket-Brigade Transversal Filter", Presented at Eurocon '71, Lausanne, Switzerland, Oct. 1971.

3. Rabiner, L.R., Schafer, R.W. and Radar, C.M., "The Chirp-Z Transform Algorithm and Its Application", Bell System Technical Journal, May-June 1969, p. 1249.

4. Perry, R.P. and Kaiser, H.W., "Digital Step Transform Approach to Airborne Radar Processing", NAECON '73 RECORD, p. 280.

5. Boyle, W.S. and Smith, G.E., "Charge Coupled Semiconductor Devices", Bell System Technical Journal, p. 587, April 1970.

6. Amelio, G.F., Thompsett, M.F., and Smith, G.E., "Experimental Verification of the Charge Coupled Device Concept", Bell System Technical Journal, p. 593, April 1970.

7. Broderson, R.W., et al, "500-Stage CCD Transversal Filter for Spectrum Analysis", IEEE, Ed-23, February 1976.

8. Hewes, C.R., "A Self Contained 800-Stage CCD Transversal Filter", CCD Conference, San Diego, October 1975.

9. Kosonocky, W.F. and Carnes, J.E., "Basic Concepts of Charge Coupled Devices", RCA Review, p. 566, September 1975.

10. Sequin, C.H. and Tompsett, M.F., "Charge Transfer Devices", Academic Press, 1975.

11. Jespers, P.G., ed, "NATO Advanced Study Institute on Solid State Imaging Proceedings", p. 249, 1976.

12. Camenzind, H.R., "Electronic Integrated Systems Design", Van Nostrand Reinhold, p. 85, 1972.

13. Sequin, C.H. and Thompsett, M.F., "Charge Transfer Devices", Academic Press, 1975, p. 68.

14. Mohsen, A.M., et al, "A 64-K Bit Block Addressed Charge Coupled Memory", IEEE, Ed-23, February 1976.

15. Kosonocky, W.F. and Carnes, J.E., "Two-Phase Charge Coupled Device", NASA Final Report, NAS 1-10983, February 1972, p. 7.

16. Thompsett, M.F., CCD Technology International Conference on Technology and Applications of CCD's, Edinburgh, Scotland, 1974, p. 79.

17. Carnes, J.E. and Kosonocky, W.F., "Noise Sources in Charge Coupled Devices", RCA Review, June 1972.

18. Brodersen, R.W. and Emmons, S.P., "Noise in Buried Channel CCD", IEEE, Ed-23, February 1976, p. 215.

19. Mohsen, A.M. and Thompsett, M.F., "The Effects of Bulk Traps on the Performance of BCCD", IEEE, Ed-21, p. 701.

20. Carnes, J.E., et al, "Experimental Measurements of Noise in CCD's", RCA Review, December 1973.

21. Kittel, C., "Introduction to Solid State Physics", Wiley, 1966, p. 306.

22. Sze, S.M., "Physics of Semiconductor Devices", Wiley, 1969, p. 28.

23. Wang, S., "Solid-State Electronics", McGraw-Hill, 1966, p. 150.

24. Dyck, R.H. and Jack, M.D., "Low Light Level Performance of a Charge-Coupled Area Imaging Device", CCD '74, Edinburgh, Scotland, p. 154.

25. "Electro-Optical Systems Design", May 1977.

26. Carnes, J.E., et al, "Effects of Radiation on CCD's", RADC-TR-76-285, September 1976.

27. MacLenna, D.J. and Mavor, J., "Novel Technique for the Linearization of Charge-Coupled Devices", Electronics Letter 11, No. 10, pp. 222-3, 1975.

28. Gandolfo, D.A., Boornard, A., Herrmann, E.P., and Steppes, D.B., "High Speed CCD Scanned Photosensor for Gigabit Recording Applications", RCA Review, December 1976, Vol. 37, No. 4.

29. Box, G.E.P. and Muller, M.E., "A Note on the Generation of Normal Deviates", Annals of Mathematical Statistics, XXIX (1958), p. 610-11.

30. McClellan, J.H., Parks, T.W., and Rabiner, L.R., "A Computer Program for Designing Optimum FIR Linear Phase Digital Filters", IEEE Audio and Electroacoustics, Vol. AU-21, p. 506-525, December 1973.

31. Lampe, D.R., et al, "An Electrically Programmable LSI Transversal Filter for Discrete Analog Signal Processing", 1973 CCD Applications Conference Proceedings, Naval Electronics Laboratory Center, San Diego, California.

32. Harp, J.G., et al, " Analogue Correlator Using Charge Coupled Devices", 1975 International Conference on the Application of CCD's, Sponsored by Naval Electronics Laboratory Center, Oct. 1975.

33. Zimmerman, T.A., and Barbe, D.F., "A New Role for Charge-Coupled Devices: Digital Signal Processing", Electronics, March 31, 1977.

34. Chan, Y.T., French, B.T., and Green, P.E., "Extremely High Speed CCD Analog Delay Line", 1975 International Conference of the Application of CCD's, Sponsored by Naval Electronics Laboratory Center, Oct. 1975.

35. Gradl, D.A., Groenwald, R.A., and Flanagan, T.J., "High Speed Operation of CCD's", 1975 International Conference on the Application of CCD's, Sponsored by Naval Electronics Laboratory Center, Oct. 1975.

36. Dawson, R., Carnes, J., Pridgen, J., and Preisig, J., "Charge-Coupled Devices for Communications", Final Report prepared for U.S. Army Electronics Command, Fort Monmouth, NJ, under Contract DAAB07-75-C-1323, Oct. 1976.

37. Suciu, P.I., et al, "Integrated Charge-Coupled Split Electrode Transversal Filters", IEEE Electro '77, April 1977.

APPENDIX A. COMPUTER LISTING OF DELAY LINE

```
C
C       CCD1.FTN
C
C
C
C           CCD STUDY   MODELING AND SIMULATION OF THE DEVICE
C
C
C
C***************************************************************
C***************************************************************
C
            REAL A(2),B(3)
            COMMON /RAND/G0(10)
            COMMON /BINSTR/G(50)
            COMMON /CCD/G1(1202)
            COMMON /INPUT/G2(1200)
            COMMON /VOLTS/G5(10)
            COMMON /PASS/GG(50)
            COMMON /COEFF/COEFF(600)
      10     CONTINUE
              WRITE(5,100)
      100     FORMAT(1H1'   CCD STUDY   TEST RUN'//)
              CALL TIME(A)
              CALL DATE(B)
              WRITE(5,101) B,A
      101     FORMAT(5X,'DATE:   ',3A4,5X,'TIME:    ',2A4//)
              CALL LINK('C0')
              CALL LINK('C1')
              CALL LINK('C2')
              CALL LINK('C3')
              CALL LINK('C4')
              CALL LINK('C5')
              CALL LINK('C6')
C*
C*
C*       THE FOLLOWING CODE IS USED TO FORCE THE
C*          MAIN MODULE TO CARRY THE I/O ROUTINES
C*          SEE DESCRIPTION IN FORTRAN OR LINK
C*          MANUALS
C*
C*
                       IDUM=0
             IF(IDUM.EQ.0)  GOTO 10
                READ(1'INDEX) A
                WRITE(1'INDEX) A
                READ(6,1001) II,A
                WRITE(6,1001) II,A
      1001      FORMAT(I5,E15.8,F10.0)
                  END
```

```
C*
C*
C*        CCD LINK STRUCTURE
C*
C*     CCD,CCD,CCD<CCD1,FTNLIB/L/U/E
C*
C*
C*       C0 LINK STRUCTURE
C*
C*     C0,C0<CCD.STB,C0,CCD6,CCD19,CCD31,FTNLIB/L/U/E
C*
C*
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /PASS/STAD(20),ISTAD(22),ROW(7),IRW(4)
1       CONTINUE
         IF(IJ(9).NE.9998)  CALL INSTR
         IF(IJ(21).GT.0)  CALL REPEAT
         IF(IJ(9).LT.0)  GOTO 1
          IJ(21)=IJ(21) + 1
         CALL RETURN
          END

C*
C*
C*        C1 LINK STRUCTURE
C*
C*
C*  C1,C1<CCD.STB,C1,CCD5,FTNLIB/L/U/E
C*
      COMMON /RAND/PI,PII
          PI=4.*ATAN(1.)
          PII=2.*PI
        CALL PRTVAL
        CALL RETURN
          END

C*
C*
C*        C2 LINK STRUCTURE
C*
C*
C*     C2,C2<CCD.STB,C2,CCD2,FTNLIB/L/U/E
C*
        CALL INPUT
        CALL RETURN
          END

C*
C*
C*        C3 LINK STRUCTURE
C*
C*
C*     C3,C3<CCD.STB,C3,CCD3,FTNLIB/L/U/E
C*
        CALL INITL
        CALL RETURN
          END
```

```
C*
C*
C*        C4 LINK STRUCTURE
C*
C*
C*     C4,C4<CCD,STB,C4,CCD7,CCD17,CCD18,CCD20,CCD30,FTNLIB/L/U/E
C*
          CALL SD
          CALL XRUN
          CALL RETURN
            END

C*
C*
C*        C5 LINK STRUCTURE
C*
C*
C*     C5,C5<CCD,STB,C5,CCD8,FTNLIB/L/U/E
C*
          CALL OUTP
          CALL RETURN
            END

C*
C*
C*        C6 LINK STRUCTURE
C*
C*     C6,C6<CCD,STB,C6,CCD26,CCD27,CCD28,CCD29,CCD16,FTNLIB/L/U/E
C*
C*
          CALL SETUP
          CALL RETURN
            END
```

```
C     CCD6.FTN
C
C
C
C            SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN
C
C
              SUBROUTINE INSTR
        REAL A(3)
      COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
     2               ZL(20),ISTAGE,IPRINT,ILENGT,IFILT,NRVS,IJ(20)
      COMMON /BINSTR/XXZ(30),IJL(30)
      COMMON /VOLTS/WW1,WW2,ITIME
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      COMMON /RAND/R1(4),RR(6)
         DATA A/4HTEMP,4H02.D,4HAT00/
            IJL(21)=0
            IRW(3)=0
            IJL(9)=9998
        WRITE(6,7000)
7000    FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/)
        READ(6,91) I
        IF(I.NE.0) GOTO 7005
        WRITE(6,7001)
7001    FORMAT(' NAME OF FILE XXXXXX.D '/)
        READ(6,7002) A(1),A(2)
7002    FORMAT(2A4)
7005    WRITE(5,7003) A
7003    FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
        CALL SETFIL(2,A,IER2,'DK',0)
        DEFINE FILE 2(50,64,U,IVAR)
1       WRITE(6,100)
100     FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)'//)
        READ(6,101) X
101     FORMAT(F10.0)
             IUPPER=600
             ILOWER=0
             ISTAGE=X
        IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER))  GOTO 3
          WRITE(6,201) ISTAGE,ILOWER,IUPPER
201     FORMAT(' ERROR MESSAGE  # OF STAGES TO SMALL OR TO LARGE'/
     2' # OF STAGES:  ',I4,'  LOWER LIMIT:  ',I4,' UPPER:  ',I4//)
             GOTO 1
3       WRITE(6,103)
103     FORMAT(' SD OF THE INITIAL STATE (F10.0) '/
     2' IF < 0 THEN NO BACKGROUND VOLTAGE ADDED '/)
        READ(6,101) XSD
C*
C*
C*      CHANGE 02/22/77
C*
        XXZ(3)=XSD
        IJL(1)=ISTAGE
4       WRITE(6,104)
104     FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1.)'/)
        READ(6,101) ZZ1
        IJ(1)=ZZ1
        IJL(6)=IJ(1)
        IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
```

```
      WRITE(6,108)
108   FORMAT(' AREA OF WELL IN MIL**2 '/)
      READ(6,101) ZL(5)
      WRITE(6,107)
107   FORMAT(' % OF BACKGROUND CHARGE '/
    2 '  <0 THEN SPECIFY TRANSFER LOST '/)
      READ(6,101) ZL(6)
      IF(ZL(6).LT.0.) WRITE(6,7891)
7891  FORMAT(' FRACTION LOST EACH TIME .XXXX'/)
      IF(ZL(6).LT.0.) READ(6,101)  XPERC
      IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,IJ)
      WRITE(6,109)
109   FORMAT(' CLOCK SWING VOLTAGE '/)
      READ(6,101) ZL(8)
      XXZ(1)=XPERC
      XXZ(15)=ZL(5)
      XXZ(16)=ZL(6)
      XXZ(18)=ZL(8)
      WRITE(6,9050)
9050  FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 '/)
      READ(6,91) IJL(7)
      WRITE(6,7011)
7011  FORMAT(' FFT OF OUTPUT  Y=1 N=0 '/)
      READ(6,91) IJL(30)
5     WRITE(5,1000) ISTAGE,XPERC,ZL(6),ZL(5)
1000  FORMAT(' # OF STAGES IN THE CCD ',I5/
    3' CTI OF DEVICE ',1PE15.8/
    4' % OF THE BACKGROUND CHARGE ',1PE15.8/
    4' AREA OF THE WELL (MIL**2)',1PE15.8//)
6     WRITE(6,206)
206   FORMAT(' CLOCK FREQUENCY (F10) '/)
        CLCKMX=1.E10
      READ(6,101) FCLOCK
    IF((FCLOCK.GT.0.).AND.(FCLOCK.LE.CLCKMX)) GOTO 60
      WRITE(6,1006) CLCKMX
1006  FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO 'F10.0/)
           GOTO 6
60    CONTINUE
      WRITE(5,701)  FCLOCK
701   FORMAT('   CLOCK RATE  ',1PE15.8/)
80    WRITE(6,800)
800   FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 '/)
      READ(6,101) ZZ1
        ITIME=ZZ1
      IF((ITIME.LT.0).OR.(ITIME.GT.1200))   GOTO 80
      WRITE(6,90)
90    FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1'/)
      READ(6,91) IPRINT
91    FORMAT(I1)
      WRITE(6,9008)
9008  FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1'/)
C*
C*    MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
C*
C*
      XXZ(4)=FCLOCK
      IJL(2)=IPRINT
          XMAXV=2.8
          WW1=XMAXV
      READ(6,91)     NRVS
```

```
96      WRITE(6,93)
93      FORMAT(' DURATION OF THE SIGNAL MIN=0 MAX=1200'/)
        READ(6,101) ZZ1
        ILENGT=ZZ1
        WRITE(6,7020)
7020    FORMAT(' TYPE OF SIGNAL PULSE =0 SIN = 1 '/)
        READ(6,91) IJL(29)
        IF(IJL(29).EQ.0)  GOTO 95
7022    WRITE(6,7021)
7021    FORMAT(' # OF SINUSODIALS  F10. < 5'/)
        READ(6,101) ZZ1
        IJL(28)=ZZ1
        IF((IJL(28).LE.0).OR.(IJL(28).GT.4))  GOTO 7022
        IKK=IJL(28)
        IKL=30
        DO 7023 I=1,IKK
        WRITE(6,7024) I
7024    FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL(HERTZ)'/)
        READ(6,101) ZZ1
        XXZ(IKL)=ZZ1
        WRITE(6,8025) I
8025    FORMAT(' AMPLITUDE (% OF WELL) OF THE ',I3,' SIGNAL'/)
        READ(6,101) STAD(I)
        STAD(I)=WW1*STAD(I)/100.
        WRITE(5,7030) I,ZZ1,STAD(I)
7030    FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL ',1PE15.8/
     2   ' AMPLITUDE (VOLTS) OF THE SIGNAL ',1PE15,8/)
        IKL=IKL - 1
7023    CONTINUE
        WRITE(6,8053)
8053    FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 '/)
        READ(6,101) XXZ(5)
         XXZ(5)=WW1*XXZ(5)/100.
          GOTO 9918
95      CONTINUE
        WRITE(6,92) XMAXV
92      FORMAT(' INPUT LEVEL OF SIGNAL  MAX= ',F10.3,' VOLTS'/)
        READ(6,101) XLEV
        IF((XLEV.LE.0.).OR.(XLEV.GT.XMAXV)) GOTO 95
9918    CONTINUE
        IJL(3)=ILENGT
        IJL(5)=NRVS
        XXZ(10)=XLEV
        WRITE(6,8010)
8010    FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1'/)
        READ(6,91) IJ(12)
        WRITE(6,97)
97      FORMAT(' FILTER RESPONSE COMPUTED? N=0 Y=1'/)
        READ(6,101) ZZ1
        IFILT=ZZ1
        IJL(20)=1
        WRITE(6,9033)
9033    FORMAT('  DARK CURRENT ADDED Y=0 N=1 '/)
        READ(6,91) IJ(13)
        IF(IJ(13).EQ.1)  GOTO 9036
         WRITE(6,9034)
9034    FORMAT(' AMBIENT TEMPERATURE DEGREES C '/)
         READ(6,101) ZZ1
         XXZ(26)=ZZ1 + 273.
        WRITE(5,9035) ZZ1,XXZ(26)
```

```
9035    FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,'  (K) ',F10.4/)
        WRITE(6,1701)
1701    FORMAT(' DO YOU WANT TO HOLD THE SIGNAL FOR ANY '/
     2  ' OF TIME Y=0 N=1 '/)
        READ(6,91) IJL(20)
        IF(IJL(20).EQ.1)  GOTO 9036
        WRITE(6,1702)
1702    FORMAT(' TIME(SEC) LEFT IN DELAY LINE '/)
        READ(6,101) XXZ(21)
        WRITE(6,1703)
1703    FORMAT(' FREQUENCY CLOCK SIGNAL OUT AT '/)
        READ(6,101) XXZ(22)
        WRITE(5,1704) XXZ(4),XXZ(21),XXZ(22)
1704    FORMAT(' INPUT SAMPLING RATE '1PE15.8,
     2  ' TIME LEFT IN DEVICE ',1PE15.8,
     3  ' OUTPUT SAMPLING RATE ',1PE15.8/)
9036    CONTINUE
        IJL(4)=IFILT
        IJL(17)=IJ(12)
        IJL(18)=IJ(13)
        WRITE(6,6011)
6011    FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10'/)
        READ(6,101) ZZ1
        IJL(19)=ZZ1
        IF(IJL(19).EQ.0)  GOTO 8000
        WRITE(6,6012)
6012    FORMAT(' WHICH INPUT IS TO BE CHANGED '/
     2  ' 1= # OF STAGES, 2=SURFACE/BURIED '/
     3  ' 3= AREA OF WELL, 4=STORAGE TIME (SEC) '/
     4  ' 5=CLOCK FREQUENCY,6=AMBIENT TEMPERATURE '//)
        READ(6,91) IJL(22)
          K=IJL(19)
        DO 6019 I=1,K
         WRITE(6,6013) I
6013    FORMAT(' INPUT THE ',I6,' VALUE '/)
         READ(6,101) RR(I)
6019    CONTINUE
          WRITE(5,6015) (I,RR(I),I=1,K)
6015    FORMAT(' MULTIPLE RUNS '//7(1X,I2,2X,1PE15.8))
          WRITE(6,8717)
8717    FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 '/)
        READ(6,91) IRW(1)
        IF(IRW(1).EQ.0)  GOTO 8000
        WRITE(6,6012)
        READ(6,91) IRW(2)
        K=IRW(1)
        DO 8718 I=1,K
        WRITE(6,6013) I
        READ(6,101)  ROW(I)
8718    CONTINUE
        WRITE(5,6015)  (I,ROW(I),I=1,K)
8000    WRITE(6,8001)
8001    FORMAT(' RUN WITH NOISE Y=0 N=1 '/)
        READ(6,91) IJ(3)
        IJL(8)=IJ(3)
        IF((IJ(3).LT.0).OR.(IJ(3).GT.1))  GOTO 8000
        IF(IJ(3).EQ.1)   RETURN
          K=10
        DO 9000 I=5,11
         IJ(I)=0
```


BEST AVAILABLE COPY

```
        IJL(K)=0
         K=K + 1
9000    CONTINUE
        WRITE(6,8003)
8003    FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1'/)
        READ(6,91) IJ(5)
        IJL(10)=IJ(5)
        IF(IJ(5).EQ.0)   RETURN
        WRITE(6,8004)
8004    FORMAT(' ADD IN INPUT NOISE Y=0 N=1 '/)
        READ(6,91) IJ(6)
        WRITE(6,8005)
8005    FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1'/)
        READ(6,91) IJ(7)
        WRITE(6,8006)
8006    FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1'/)
        READ(6,91) IJ(8)
        WRITE(6,8007)
8007    FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1'/)
        READ(6,91) IJ(9)
        WRITE(6,8008)
8008    FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1'/)
        READ(6,91) IJ(10)
        WRITE(6,8009)
8009    FORMAT(' ADD IN INTERFACE NOISE '/)
        READ(6,91) IJ(11)
           K=11
        DO 57 I=6,11
        IJL(K)=IJ(I)
        K=K + 1
57      CONTINUE
                  RETURN
                  END
```

BEST AVAILABLE COPY

```
C*
C*
C*      CCD19.FTN
C*
C*
C*       COMPUTES CTI FOR SURFACE AND BURIED DEVICES
C*
C*        02/22/77
C*
C*
        SUBROUTINE CTI(ZL,ZPERC,IJ)
      INTEGER IJ(5)
      REAL ZL(20)
        X=ZL(6)
      IF(IJ(1).EQ.1)   GOTO 100
       IF(X.GT.4.) GOTO 1
        ZPERC=3.6E-4
        RETURN
1      IF(X.GT.5.) GOTO 2
         ZPERC=-2.7E-4*X + 1.4E-3
         RETURN
2       IF(X.GT.10.) GOTO 3
         ZPERC=-1.E-5*X + 1.4E-4
         RETURN
3        ZPERC=3.9E-5
         RETURN
100     IF(X.GT.4.)  GOTO 101
         ZPERC=-1.6E-5*X + 1.1E-4
         RETURN
101     IF(X.GT.13.5) GOTO 102
         ZPERC=-2.1E-6*X + 5.8E-5
         RETURN
102      ZPERC=2.8E-5
         RETURN
         END
```

```
C*
C*
C*
C*      CCD31.FTN
C*
C*
C*
              SUBROUTINE REPEAT
      REAL A(3)
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /RAND/R1(4),RR(6)
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      DATA A/4HTEMP,4H02.D,4HAT00/
        CALL SETFIL(2,A,IER2,'DK',0)
        DEFINE FILE 2(50,64,U,IVAR)
        IF(IJ(21).GT.IJ(19))  GOTO 1000
            K=IJ(22)
           KK=IJ(21)
        CALL FINDER(RR,Y,K,KK)
      IF((IJ(21).EQ.1).AND.(IRW(3).EQ.0))  ROW(7)=Y
            RETURN
1000    CONTINUE
        IRW(3)=IRW(3) + 1
        IF(IRW(3).GT.IRW(1))  GOTO 2000
          K=IRW(2)
         KK=IRW(3)
        CALL FINDER(ROW,Y,K,KK)
          K=IJ(22)
         KK=7
          IJ(21)=0
         CALL FINDER(ROW,Y,K,KK)
            RETURN
2000    CONTINUE
            IJ(9)=-10000
            RETURN
              END
```

```
C*
C*
C*
C*      CCD32.FTN
C*
C*
C*
        SUBROUTINE FINDER(A,Y,K,KK)
      REAL A(2)
      COMMON /BINSTR/XX(30),IJ(30)
           X=A(KK)
        WRITE(5,1010)  K,KK,A(KK)
1010    FORMAT('  VARIABLE CHANGES ',2(I6,1X),1PE15.8)
      GOTO (10,20,30,40,50,60),K
           WRITE(6,1000) K
1000    FORMAT('  ERROR MESSAGE IN REPEAT ',I6)
          STOP
10       Y=IJ(1)
         IJ(1)=A(KK)
        RETURN
20      Y=IJ(6)
        IJ(6)=A(KK)
        RETURN
30      Y=XX(15)
        XX(15)=A(KK)
        RETURN
40      Y=XX(21)
        XX(21)=A(KK)
        RETURN
50      Y=XX(4)
        XX(4)=A(KK)
        RETURN
60      Y=XX(26) - 273.
        XX(26)=A(KK) + 273
        RETURN
         END
```

```
C*
C!      CC05.FTN
C*
C*
C*      SUBROUTINE PRINTS OUT MEANS AND SD OF THE
C*         VARIOUS NOISE RANDOM VARIABLES
C*
C*
              SUBROUTINE PRTVAL
        REAL JD,NSS
        COMMON /BINSTR/XX(30),IJL(30)
        COMMON /RAND/PI,PII,II1,II2
        COMMON /PASS/STAD(20)
C*
C*
C*          NOISE ADDED OR NOT
C*
            INOISE=IJL(8)
            IDARK=IJL(18)
C*
C*
C*      CONSTANTS NEED IN CALCULATIONS
C*
C*
C*
          XKB=8.617E-5
          AREA=XX(15)*6.4516E-6
          Q=1.602E-19
          NSS=1.E10
          C=1.E-13
          QQ=1.6498E-24
          TD=100.E-6
          XD=1.E-4
          SIGMA=1.E-15
          VTH=8.E5
          XNST=5.E9
          XNNN=5.E14
          XLN=0.05609
          TEMP=XX(26)
          FCLOCK=XX(4)
          FCLOK2=XX(22)
C*
C*
C*    INPUT NOISE
C*
C*     MEAN=0
C*
C*      VAR= XKB*TEMP*C/Q**2
C*
C*
C*
          X=XKB*TEMP
          XX(6)=SQRT(2.*X*C/(3.*Q))
C!
C*
C*        OUTPUT NOISE
C*
C*    SAME AS ABOVE
C*
```

```
C*
            XX(9)=XX(6)
C*
C*
C*
C*         FAST INTERFACE
C*
C*
C*
C           MEAN=0
C           SD=SQRT(0.7*K*TEMP*NSS*AREA)
C
C
            XX(19)=SQRT(0.7*X*NSS*AREA)
C*
C*
C*
C*          FILTER NOISE
C*
C*
C*           MEAN =  0.0061
C*
C*           SD   = 0.07
C*
            XX(20)=0.0061
            XX(17)=0.07
C*
C*
C*
C*          DARK CURRENT
C*
C*
            IF(XX(26).LT.250.)  GOTO 50
              XNI=1.21/(8.617E-5*TEMP)
              XNI=EXP(-XNI)
              XNI=XNI*1.5E33
              XNI=XNI*TEMP**3
              XNI=SQRT(XNI)
                GOTO 51
50          CONTINUE
              XNI=53228827.58
51          CONTINUE
              GBI=XNI*XNI*XLN/(XNNN*TD)
              GSI=0.5*XNI*SIGMA*VTH
              GDI=XNI*XD/(2.*TD)
              XX(25)=10000.
              STAD(20)=GBI
              STAD(19)=GSI
              STAD(18)=GDI
              STAD(17)=AREA/(FCLOCK*2.)
              XX(24)=AREA
              STAD(16)=XNST
              STAD(15)=QQ/1.0363E-5
            IF(IDARK.EQ.1) XX(25)=0.
            IF(IDARK.EQ.2) WRITE(5,8010) GBI,GSI,GDI,TOTALI
8010        FORMAT(' INDIVIDUAL SOURCES OF DARK CURRENT '/
     2       6(3X,1PE15.8))
C*
C*          SHOT NOISE
C*
```

```
C*      MEAN=0.
C*
C*      SD= SQRT(JD*AREA/Q*FCLOCK)
C*
C*
          JD=GBI + GSI*XNST + GDI
          JD=JD*STAD(15)
          XX(7)=SQRT(JD*AREA/(Q*FCLOCK))
          IF(IJL(20).EQ.0) XX(23)=SQRT(JD*AREA/(Q*FCLOK2))
C*
C*        PRINT OUT THE MEANS AND SD
C*
C*
          IF(INOISE.EQ.1)  RETURN
          WRITE(5,9088)  XX(25)
 9088     FORMAT(' DARK CURRENT ELECTRONS ADDED PER '
     2 'TRANSFER ',1PE15.8//)
C*
            Z=0.
          WRITE(5,2) Z,XX(6)
          WRITE(5,3) Z,XX(7)
          WRITE(5,5) Z,XX(9)
          WRITE(5,6) XX(20),XX(17)
          WRITE(5,10) Z,XX(19)
          WRITE(5,7) (IJL(I),I=10,16)
 7        FORMAT(' STATUS OF THE NOISE SOURCES'//
     2' SELECT THE NOISE INPUTS Y=1 N=0 ',I2/
     3' ADD IN INPUT NOISE Y=0  N=1 ',I2/
     4' ADD IN SHOT NOISE Y=0 N=1 ',I2/
     5' ADD IN TRANSFER NOISE  Y=0 N=1 ',I2/
     6' ADD IN OUTPUT NOISE Y=0 N=1 ',I2/
     7' ADD IN FILTER NOISE Y=0  N=1 ',I2/
     8' ADD IN INTERFACE NOISE Y=0 N=1 ',I2//)
 2        FORMAT(' MEAN OF THE INPUT NOISE     ',1PE15.8,
     2 '    SD   ',1PE15.8/)
 3        FORMAT(' MEAN OF THE SHOT NOISE      ',1PE15.8,
     2 '    SD   ',1PE15.8/)
 4        FORMAT(' MEAN OF THE TRANSFER NOISE ',1PE15.8,
     2 '    SD   ',1PE15.8/)
 5        FORMAT(' MEAN OF THE OUTPUT NOISE   ',1PE15.8,
     2 '    SD   ',1PE15.8/)
 6        FORMAT(' MEAN OF THE FILTER ERROR    ',1PE15.8,
     2 '    SD   ',1PE15.8/)
 10       FORMAT(' MEAN OF THE INTERFACE NOISE  ',1PE15.8,
     2           ' SD    ',1PE15.8/)
                RETURN
               END
```

```
C
C     CCD2.FTN
C
C
C
C
C          SUBROUTINE GENERATES THE INPUT SIGNAL TO THE CCD
C
C
C          ASSUMES THAT MAXIMUM VOLTAGE IS 2 VOLTS (XMAXV)
C          WHICH CORRESPONDS TO 100000 ELECTRONS (XMAXEL)
C
C          ITIME IS THE CCD RUN TIME
C
                    SUBROUTINE INPUT
        REAL A(30)
      COMMON /INPUT/ELECTR(1200)
      COMMON /BINSTR/XZ(30),IJ(30)
      COMMON /VOLTS/XMAXV,XMAXEL,ITIME
      COMMON /CCD/HOLD(1200)
      COMMON /RAND/PI,PII
      COMMON /PASS/STAD(20)
C
C
C       TRIAL RUN   IMPULSE AT TIME  ZERO
C
C
C*
C*     02/18/77 CHANGE IN FULL WELL ELECTRON COUNT
C*
C*      CLOCK SWING
C*
        CS=XZ(18)
        AREA=XZ(15)
        COUL=2.625E-13
        ELECR=6.281E+18
        XMAXEL=AREA*COUL*ELECR*CS
        IF(IJ(6).EQ.1) XMAXEL=XMAXEL/2.
           XZ(2)=XZ(16)*XMAXEL/100.
        WRITE(5,1000) XMAXV,XMAXEL,CS,IJ(6)
1000  FORMAT(' MAXIMUM INPUT VOLTAGE ',1PE15.8,
     25X,'CORRESPONDS TO MAXIMUM NO. OF ELECTRONS ',1PE15.8/
     31X,'CLOCK SWING VOLTAGE ',1PE15.8/
     4' SURFACE(FAT ZERO) 0   OR BURIED(SLIM ZERO) 1 ',I2//)
             CONST=XMAXEL/XMAXV
             CC2=1./CONST
        WRITE(5,2000) XZ(10),IJ(3),XZ(5)
2000    FORMAT(' VOLTAGE OF THE SIGNAL ',F10.4,'  LENGTH ',
     2'OF THE SIGNAL ',I6/
     3' BIAS VOLTAGE ADDED TO INPUT ',F10.4/)
           AVE=XZ(2)
           SD=XZ(3)
        IF(SD.LT.0.)   GOTO 10
           K=31
        DO 4 I=1,ITIME
           IF(K.LE.30)  GOTO 1
           K=1
8001    CONTINUE
           READ(1,END=8000,ERR=8000) A
```

BEST AVAILABLE COPY

```
1           CONTINUE
         ELECTR(I)=A(K)*SD + AVE
              K=K + 1
4        CONTINUE
              GOTO 20
10       DO 15 I=1,ITIME
           ELECTR(I)=0.
15       CONTINUE
20       CONTINUE
         IF(IJ(3).EQ.0)  RETURN
            I1=IJ(3)
            VOLT=XZ(10)
         IF(IJ(29).EQ.1) GOTO 7000
          IF(IJ(17).EQ.1)  GOTO 26
C*
C*    NON LINEAR INPUT CHARACTERISTC
C*
C*       03/29/77
C*
           IF(VOLT.GT.0.420)  GOTO 22
            VOLT=2.783*VOLT - 0.082
            GOTO 26
22          IF(VOLT.GT.1.280) GOTO 24
            VOLT=0.98*VOLT + 0.666
            GOTO 26
24            VOLT=0.572*VOLT + 1.183
26          CONTINUE
         DO 25 I=1,I1
           ELECTR(I)=VOLT*CONST + ELECTR(I)
          IF(ELECTR(I).GT.XMAXEL) ELECTR(I)=XMAXEL
25       CONTINUE
         IF(IJ(17).EQ.0) WRITE(5,1050)  VOLT
1050     FORMAT(' NON LINEAR INPUT VOLTAGE ',1PE15.8/)
                RETURN
7000     CONTINUE
          VOLTM2=XZ(5)
         IK=IJ(28)
         SAMPL=1./XZ(4)
           TIME=0.
         DO 7050 II=1,I1
           HOLD(II)=0.
           IK2=30
          DO 7040 I=1,IK
            FREQ=XZ(IK2)*PII*TIME
            HOLD(II)=HOLD(II) + STAD(I)*SIN(FREQ)
             IK2=IK2 - 1
7040       CONTINUE
             TIME=TIME + SAMPL
7050      CONTINUE
          DO 7060 II=1,I1
           VOLT=HOLD(II) + VOLTM2
           VOLT=VOLT + ELECTR(II)*CC2
          IF(IJ(17).EQ.1)  GOTO 7059
           IF(VOLT.GT.0.420)  GOTO 7051
            VOLT=VOLT*2.783 - 0.082
            GOTO 7059
7051       IF(VOLT.GT.1.280)  GOTO 7052
             VOLT=VOLT*0.98 + 0.666
             GOTO 7059
7052         VOLT=VOLT*0.572 + 1.183
```

```
7059      CONTINUE
            ELECTR(II)=VOLT*CONST
          IF(ELECTR(II).GT.XMAXEL)  ELECTR(II)=XMAXEL
7060        CONTINUE
              STAD(5)=XZ(5)*CONST
                RETURN
8000        REWIND 1
          GOTO 8001
            END
```

BEST AVAILABLE COPY

```
C
C
C       CCO3.FTN
C
C
C
C
C         SUBROUTINE INITIALIZES CCD FOR INPUT DATA
C
C
C
C
                SUBROUTINE INITL
          REAL AA(30)
        COMMON /CCD/CCOW(2,601)
        COMMON /BINSTR/XJ(30),IJ(30)
        COMMON /VOLTS/XMAXV,XMAXE
        COMMON /PASS/STAD(20)
              ISTAGE=IJ(1)
              IPRINT=IJ(2)
              INOISE=IJ(8)
          IF(IJ(29).EQ.1)  GOTO 7000
              AVE=XJ(2)
                SD=XJ(3)
          IF(SD.LT.0.)  GOTO 100
          WRITE(5,505) AVE,SD
505       FORMAT('  MEAN VALUE OF THE INITIAL STATES ',1PE15.8/
     2    ' SD OF THE INITIAL STATES ',1PE15.8/)
                I=1
1         READ(1,END=8000,ERR=8000) AA
                K=1
2               CONTINUE
          CCDW(2,I)=AA(K)*SD + AVE
             RES=CCDW(2,I)*XJ(1)
             CCDW(1,I)=RES
             CCDW(2,I)=RES
                I=I + 1
                K=K + 1
          IF(I.GT.ISTAGE)  GOTO 3
          IF(K.GT.30)      GOTO 1
                GOTO 2
3           CONTINUE
          IF(IPRINT.NE.1) RETURN
          WRITE(5,1000) (I,I=1,ISTAGE)
1000      FORMAT(15X,'STAGES   '/(13I10))
          WRITE(5,1001) (CCDW(1,I),CCDW(2,I),I=1,ISTAGE)
1001      FORMAT(12(1X,F10.2))
                RETURN
100       DO 110 I=1,ISTAGE
            CCOW(1,I)=0.
            CCDW(2,I)=0.
110       CONTINUE
200       WRITE(5,201)
201       FORMAT(' NO BACKGROUND VOLTAGE ADDED '/)
          RETURN
7000         CONTINUE
          BIAS=STAD(3)
          RES=BIAS*XJ(1)
          BIAS=BIAS - RES
          DO [illegible] I=1,ISTAGE
            CCDW(1,I)=RES
```

```
      CCDW(2,I)=RES
7001  CONTINUE
      WRITE(5,7010)  RES,BIAS
7010  FORMAT(' BIAS TERMS ADDED TO WELLS ',2(2X,1PE15.8)/)
        RETURN
8000  REWIND 1
      GOTO 1
          END
```

BEST AVAILABLE COPY

```
C*
C*      CCD7.FTN
C*
C
C
C         SUBROUTINE DOES THE BOOKKEEPING FOR THE CCD2 ARRAY
C                VERSUS TIME
C
C
                 SUBROUTINE XRUN
        REAL A(30),B(30)
      COMMON /VOLTS/Q1,Q2,ITIM
      COMMON /CCD/CCDW(2,601)
      COMMON /INPUT/ELECTR(1200)
      COMMON /BINSTR/XPERC,XMEAN,XSQ,FCLOCK,FBAND,XZ(25),ISTAGE
     2           ,IPRINT,ILENGT,IFILT,ILJ(3),INOISE,IJJ(20)
      COMMON /PASS/STAD(20),ISTAD(20),IVAR
               LL=ISTAGE + 1
C*
C*      SHOT NOISE
C*      INPUT NOISE
C*      TRANSFER NOISE  CHANGED  03/23/77
C*      INTERFACE NOISE ADDED 03/24/77
C*
C*
        ISTART=1
             IPP=1
             I3=0
             I4=0
             IJJ(17)=0
          DARK=XZ(20)
        IF(DARK.EQ.0.)  GOTO 5000
             I3=31
          GBI=STAD(20)
          GSI=STAD(19)
          GDI=STAD(18)
          GG=GBI + GDI
          CONST=STAD(17)
          XNST=STAD(16)
            CUR=STAD(15)
           G1=CUR*GBI
           G2=CUR*GSI
           G3=CUR*GDI
 5000   CONTINUE
        IF(INOISE.EQ.1)  GOTO 8000
             SDINPT=STAD(1)
             SDMIDL=STAD(2)
             SDTRAN=SQRT(2.*XPERC)
             INPT=ISTAD(1)
             IMIDL=ISTAD(2)
               I3=31
 8000   CONTINUE
       IF(IFILT.EQ.1) CALL COEFFS
           ILL=ITIM
             ITIME=ITIM + ISTAGE
        IF(IJJ(12).EQ.0)  ITIME=ISTAGE
             IEND=1
             IBEGIN=3
 2329   CONTINUE
```

```
            DO 1 I=ISTART,ITIME
              IF(I.EQ.1)  GOTO 7002
               IBEGIN=I - 1
                IEND=I - ILL
              IF(IBEGIN.GT.ISTAGE)  IBEGIN=ISTAGE
              IF(IEND.GT.ISTAGE)  IEND=ISTAGE
              IF(IEND.LE.0)  IEND=1
                             CCDW(1,LL)=0.
              J=IBEGIN
            IF(IPRINT .NE.1)  GOTO 25
              WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
      1001  FORMAT(I4,(6(1X,E15.8)))
      25     CONTINUE
              DO 2 K=1,ISTAGE
                 JJ=J + 1
C*
C*        FIND RESIDUE AT CLOCK PULSE 2 IN EACH WELL
C*        TRANSFER REMAINING CHARGE TO WELL AT CLOCK 1
C*        LEAVE RESIDUE IN OLD WELL AT CLOCK 2
C*
C*
                RES=XPERC*CCDW(2,J)
                CCDW(1,JJ)=CCDW(1,JJ) + CCDW(2,J) - RES
             IF(DARK.EQ.0.)  GOTO 5010
             IF(I3.LE.29)  GOTO 5001
               I3=1
      3001  CONTINUE
              READ(1,END=3000,ERR=3000) A
      5001    CONTINUE
             RAY=SQRT(A(I3)**2 + A(I3 + 1)**2)
             RAYY=XNST*RAY
             RAY=RAYY*G2
            DARKK=CONST*(GSI*RAYY + GG)
             CCDW(1,JJ)=CCDW(1,JJ) + DARKK
                GSUM=RAY + G1 + G3
            IF(I.LT.3)  WRITE(5,5002)  I,G1,RAY,G3,GSUM
      5002  FORMAT(' CURRENT DENSITIES ',I6,6(1X,E15.8))
            IF(I.LT.6) WRITE(5,5003)  I,DARKK
      5003  FORMAT(' ELECTRONS ADDED PER CLOCK ',I6,1X,E15.8)
              I3=I3 + 2
      5010  CONTINUE
                IF(IJJ(5).EQ.0) XRES=CCDW(2,J)
                CCDW(2,J)=RES
            IF(INOISE.EQ.1)  GOTO 8001
              IF(IMIDL.EQ.0)  GOTO 8001
C*
C*          ADD IN NOISE SOURCES OF MIDDLE REGION
C*            SHOT INTERACE*2
C*
                  IF(I3.LE.30)  GOTO 10
                     I3=1
      3011  CONTINUE
                   READ(1,END=3010,ERR=3010) A
      10          CONTINUE
              CCDW(1,JJ)=CCDW(1,JJ) + A(I3)*SDMIDL
                  I3=I3 + 1
      8001  CONTINUE
C*
C*          TRANSFER NOISE ADDED IN ONE PER TRANSFER
C*
```

```
              IF(INOISE.EQ.1)  GOTO 8005
              IF(IJJ(5).EQ.1)  GOTO 8005
                   IF(I3.LE.30)  GOTO 11
                     I3=1
      3021    CONTINUE
                    READ(1,END=3020,ERR=3020) A
      11            CONTINUE
                   RES=XRES
              IF(RES.LT.0.)  RES=-RES
                XRES=SQRT(RES)*SDTRAN*A(I3)
                     I3=I3 + 1
                 CCDW(2,JJ)=CCDW(2,JJ) + XRES
                 CCDW(1,JJ)=CCDW(1,JJ) - XRES
      8005     CONTINUE
              IF(CCDW(1,JJ).GT.Q2)   CCDW(1,JJ)=Q2
                IF(J.LE.IEND)  GOTO 7001
                J=J - 1
      2         CONTINUE
      7001    CONTINUE
                IF(I.LE.ISTAGE) GOTO 7002
                 IF(IFILT.EQ.1)  GOTO 7002
                I4=I4 + 1
                 B(I4)=CCDW(1,LL)
                 IJJ(17)=IJJ(17) + 1
                IF(I4.LT.30)  GOTO 7002
                 WRITE(2'IPP) B
                 IPP=IPP + 1
                 I4=0
      7002     CONTINUE
               IF(I.GT.ILL)  GOTO 21
                  CCDW(1,1)=CCDW(1,1) + ELECTR(I)
              IF(INOISE.EQ.1)  GOTO 8002
                  IF(INPT.EQ.0)  GOTO 8002
      C*
      C*      ADD IN INPUT NOISE SOURCES
      C*        SHOT INPUT INTERFACE
      C*
      C*
                    IF(I3.LE.30)  GOTO 20
                       I3=1
      3031    CONTINUE
                     READ(1,END=3030,ERR=3030) A
      20            CONTINUE
                CCDW(1,1)=CCDW(1,1) + A(I3)*SDINPT
                     I3=I3 + 1
      8002    CONTINUE
               IF(CCDW(1,1).GT.Q2) CCDW(1,1)=Q2
              IF(IPRINT.NE.1) GOTO 21
              WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
      21      CONTINUE
                    J=I
               IF(IBEGIN.GE.ILL) IEND=IEND + 1
               IF(J.GT.ISTAGE) J=ISTAGE
                 IF(I.EQ.ITIME)  GOTO 1
                DO 3 K=1,ISTAGE
      C*
      C*
      C*      FIND RESIDUE AT CLOCK 1 WELLS
      C*      TRANSFER REMAINING TO CLOCK 2 WELLS
      C:      LEAVE THE RESIDUE IN CLOCK 1 WELL
```

```
      C*
      C*
                    RES=XPERC*CCDW(1,J)
                    CCDW(2,J)=CCDW(2,J) + CCDW(1,J) - RES
                    IF(IJJ(5).EQ.0) XRES=CCDW(1,J)
                     CCDW(1,J)=RES
                  IF(DARK.EQ.0.)  GOTO 5020
                  IF(I3.LE.29)  GOTO 5021
                   I3=1
      3041      CONTINUE
                   READ(1,END=3040,ERR=3040) A
      5021        CONTINUE
                   RAY=SQRT(A(I3)**2 + A(I3+1)**2)
                   RAYY=RAY*XNST
                   DARK=CONST*(GSI*RAYY + GG)
                   CCDW(2,J)=CCDW(2,J) + DARK
      5020       CONTINUE
                IF(INOISE.EQ.1)  GOTO 8003
                   IF(IMIDL.EQ.0)  GOTO 8003
      C*
      C*        ADD IN MIDDLE NOISE SOURCES
      C*        SHOT 2*INTERFACE
      C!
      C*
                     IF(I3.LE.30)  GOTO 30
                      I3=1
      3051      CONTINUE
                      READ(1,END=3050,ERR=3050) A
      30             CONTINUE
                CCDW(2,J)=CCDW(2,J) + A(I3)*SDMIDL
                      I3=I3 + 1
      8003      CONTINUE
      C*
      C*        ADD IN TRANSFER NOISE
      C*
                   IF(INOISE.EQ.1)   GOTO 8006
                   IF(IJJ(5).EQ.1)   GOTO 8006
                     IF(I3.LE.30)  GOTO 35
                       I3=1
      3061      CONTINUE
                      READ(1,END=3060,ERR=3060) A
      35             CONTINUE
                         RES=XRES
                    IF(RES.LT.0.)  RES=-RES
                    XRES=SDTRAN*SQRT(RES)*A(I3)
                     I3=I3 + 1
                    CCDW(2,J)=CCDW(2,J) - XRES
                    CCDW(1,J)=CCDW(1,J) + XRES
      8006      CONTINUE
                IF(CCDW(2,J).GT.Q2) CCDW(2,J)=Q2
                  IF(J.LE.IEND)  GOTO 99
                        J=J -1
      3           CONTINUE
      99        CONTINUE
                IF(IPRINT.NE.1) GOTO 22
                   WRITE(5,1000)    (CCDW(1,J),CCDW(2,J),J=1,ISTAGE)
      1000      FORMAT(6(2X,E15.8))
      22        CONTINUE
               IF((IFILT.EQ.1).AND.(I.GE.ISTAGE))  CALL FILTER(A,B,I3,I4,I,IPP)
      1         CONTINUE
```

```
            IF(IJJ(12).EQ.1) GOTO 2330
            IF(ISTART.NE.1)  GOTO 2330
            CALL SETTER(XNST,GSI,GG,CONST,ITIME,ISTART,ISTAGE,ITIM)
            GOTO 2329
      2330  CONTINUE
            IF(I4.NE.0)  WRITE(2'IPP) B
                    RETURN
      3000  REWIND 1
            GOTO 3001
      3010  REWIND 1
            GOTO 3011
      3020  REWIND 1
            GOTO 3021
      3030  REWIND 1
            GOTO 3031
      3040  REWIND 1
            GOTO 3041
      3050  REWIND 1
            GOTO 3051
      3060  REWIND 1
            GOTO 3061
                    END
```

```
      C*
      C*
      C*    CCD17.FTN
      C*
      C*    SUBROUTINE LOADS UP THE WEIGTHS FOR A FILTER
      C*
      C*
                SUBROUTINE COEFFS
          COMMON /BINSTR/ZL(30),ISTAGE
          COMMON /COEFF/COEFF(600)
            WRITE(5,1000)
      1000  FORMAT(1H1/'     FILTER WEIGHTS '/)
               DO 1 I=1,ISTAGE
                READ(4,1001) COEFF(I)
      1001  FORMAT(E15.8)
                WRITE(5,1003)  I,COEFF(I)
      1003  FORMAT(I6,3X,E15.8)
                CONTINUE
      1
              WRITE(5,1002) ZL(11)
      1002  FORMAT('  % ERROR PER WEIGHT 'F10.3//)
                   RETURN
                   END
```

```
C*
C*      CCD18.FTN
C*
C*
C*      SUBROUTINE COMPUTES THE FILTER RESPONSE PER PULSE
C*
C*
C*
                  SUBROUTINE FILTER(A,B,I1,I4,J,IPP)
            REAL A(1),B(1)
            COMMON /BINSTR/XL(30),ISTAGE,IJJ(6),INOISE,IJ(20)
            COMMON /CCD/CCDW(2,601)
            COMMON /COEFF/COEFF(600)
              SD=XL(17)
              ERR=1. + XL(11)
              XSUM=0.
            DO 5 I=1,ISTAGE
                XSUM=XSUM + CCDW(2,I)*COEFF(I)*ERR
              IF(INOISE.EQ.1) GOTO 5
               IF(IJ(7).EQ.1)  GOTO 5
                  IF(I1.LE.30)  GOTO 1
      2       CONTINUE
                    I1=1
                  READ(1,END=1000,ERR=1000) A
      1          CONTINUE
                XSUM=XSUM + A(I1)*SD*CCDW(2,I)
                    I1=I1 + 1
      5     CONTINUE
              IF(J.LE.ISTAGE)  RETURN
                I4=I4 + 1
              B(I4)=XSUM
              IJ(17)=IJ(17) + 1
              IF(I4.LT.30)  RETURN
                I4=0
              WRITE(2'IPP) B
                IPP=IPP + 1
               RETURN
      1000    CONTINUE
               REWIND 1
              GOTO 2
                 END
```

```
C*
C*
C*      CCD20.FTN
C*
C*
        SUBROUTINE SD
      COMMON /BINSTR/XX(30),IJ(20)
      COMMON /PASS/STAD(20),ISTAD(20)
C*
C*
C*      LOADS APPROPRIATE NOISE SOURCES IN SDS
C*
C*
        IF(IJ(8).EQ.1) RETURN
      SDINPT=XX(6)
      SDSHOT=XX(7)
      SDOUTP=XX(9)
      SDINTR=XX(19)
C*
C*      CHECK TO SEE IF ALL SOURCES ARE ADDED IN
C*
              ISTAD(1)=0
              ISTAD(2)=0
              ISTAD(3)=0
        IF(IJ(10).EQ.1)  GOTO 10
              S1=SDSHOT*SDSHOT
              S2=SDINTR*SDINTR
C*
C*     INPUT SD
C*
              STAD(1)=SQRT(SDINPT*SDINPT + S1 + S2)
                 ISTAD(1)=1
C*
C*        MIDDLE NOISE SOURCES MINUS TRANSFER
C*
              STAD(2)=SQRT(S1 + 2.*S2)
                   ISTAD(2)=1
C*
C*      OUTPUT NOISE SOURCES
C*
              STAD(3)=SQRT(S1 + S2 + SDOUTP*SDOUTP)
                   ISTAD(3)=1
                RETURN
10      CONTINUE
C*
C*      COMPUTE INPUT IF NEEDED
C*
              VAR=0.
        IF(IJ(11).EQ.1)  GOTO 15
              VAR=SDINPT*SDINPT
              ISTAD(1)=1
15      IF(IJ(12).EQ.1)  GOTO 20
              VAR=VAR + SDSHOT*SDSHOT
              ISTAD(1)=1
20      IF(IJ(16).EQ.1)  GOTO 25
              VAR=VAR + SDINTR*SDINTR
              ISTAD(1)=1
25      IF(ISTAD(1).EQ.1) VAR=SQRT(VAR)
              STAD(1)=VAR
```

```
C*
C*
C*      COMPUTE MIDDLE SD IF NEEDED
C*
             VAR=0.
        IF(IJ(12).EQ.1)  GOTO 30
             VAR=SDSHOT*SDSHOT
             ISTAD(2)=1
30      IF(IJ(16).EQ.1)  GOTO 35
             VAR=VAR + 2.*SDINTR*SDINTR
             ISTAD(2)=1
35      IF(ISTAD(2).EQ.1)  VAR=SQRT(VAR)
             STAD(2)=VAR
C*
C*
C*       COMPUTE OUTPUT SD IF NEEDED
C*
             VAR=0.
        IF(IJ(12).EQ.1)  GOTO 40
             VAR=SDSHOT*SDSHOT
             ISTAD(3)=1
40      IF(IJ(14).EQ.1)  GOTO 45
             VAR=VAR + SDOUTP*SDOUTP
             ISTAD(3)=1
45      IF(IJ(16).EQ.1)  GOTO 50
             VAR=VAR + SDINTR*SDINTR
             ISTAD(3)=1
50      IF(ISTAD(3).EQ.1)   VAR=SQRT(VAR)
             STAD(3)=VAR
             RETURN
             END
C*
C*
C*      CCD30.FTN
C*
C*
C*
        SUBROUTINE SETTER(XNST,GSI,GG,CON,ITIME,ISTART,ISTAGE,ITIM)
        REAL A(30)
        COMMON /BINSTR/XX(30),IJ(30)
        COMMON /CCO/CCDW(2,601)
          CONST=XX(24)*XX(21)
            I4=31
          DO 100 I=1,ITIME
           IF(I4.LE.29)  GOTO 1
               I4=1
            READ(1) A
1          CONTINUE
           RV=SQRT(A(I4)**2 + A(I4+1)**2)
           RV=RV*XNST
           DARK=CONST*(GSI*RV+GG)
           CCDW(2,I)=CCDW(2,I) + DARK
            I4=I4 + 2
100       CONTINUE
          ISTART=ISTAGE + 1
          ITIME=ITIM + ISTAGE
          IF(XX(4).EQ.XX(22))   RETURN
          CON=XX(24)/(XX(22)*2.)
          IF(IJ(12).EQ.1)  RETURN
            XX(7)=XX(23)
          CALL SD
            RETURN
            END
```

```
C
C         CCD8.FTN
C
C
C
C         SUBROUTINE PRINTS OUT INITIAL AND FINAL ARRAYS
C
C
C
                SUBROUTINE OUTP
        REAL A(30),BB(30)
      COMMON /INPUT/ELECTR(1200)
      COMMON /VOLTS/XMAXV,XMAXEL,ITIME
      COMMON /BINSTR/XZ(30),IJ(2),ILT,IFILT,ILL(3),INOISE,IJL(20)
      COMMON /PASS/STAD(20),ISTAD(20)
      COMMON /CCD/A,BB,XMAX,XMIN,AVE,VAR,X1,XXIN,VMAXO,XXOUT,SD
C*
C*
C*      MAX OUTPUT VOLT IS 100 MILLEVOLTS
C*        THIS INCLUDES THE CLOCK VOLTAGE
C*
C*      SO MAKE THE MAXIMUM NON CLOCK VOLTAGE
C*         48 MILLEVOLTS
C*
C*
          NUMB=IJL(17)
           J=1
           I2=31
                  XXIN=XMAXV/XMAXEL
                  VMAXO=48.E-3
                  XXOUT=VMAXO/XMAXEL
                 K=31
                 SD=STAD(3)
C*
C*     FOLLOWING CODE IS WRITEN THIS WAY SINCE THERE
C*     IS NO OVERSTRIKE ON THE LINEPRINTER
C*
        IF(IFILT.NE.1) WRITE(5,500)
        IF(IFILT.EQ.1) WRITE(5,501)
500     FORMAT(1H1/'         (OUTPUT MINUS THE CLOCK VOLTAGE) '//
     2  16X,'VOLTS',28X,'ELECTRONS'/
     3  11X,'INPUT',5X,'OUTPUT',19X,'INPUT',6X,'OUTPUT'/
     4  1X,60(1H-))
501     FORMAT(1H1/'         (OUTPUT MINUS THE CLOCK VOLTAGE) '//
     2  16X,'VOLTS',28X,'ELECTRONS',32X,'FILTER'/
     3  11X,'INPUT',5X,'OUTPUT',19X,'INPUT',6X,'OUTPUT',22X,'VOLTS',
     4  6X,'ELECTRONS'/
     5  1X,104(1H-))
          IPP=0
        DO 100 I=1,NUMB
          X1=ELECTR(I)*XXIN
        IF(I2.LE.30)  GOTO 1
          I2=1
        IF(IPP.GT.0)  WRITE(2'IPP) BB
          IPP=IPP + 1
          READ(2'IPP) BB
1       CONTINUE
        IF(INOISE.EQ.1) GOTO 3
        IF(ISTAD(3).EQ.0)  GOTO 3
        IF(K.LE.30)  GOTO 2
3001    CONTINUE
```

```
          K=1
         READ(1,END=3000,ERR=3000) A
2       CONTINUE
        BB(I2)=BB(I2) + A(K)*SD
3       CONTINUE
        X2=BB(I2)*XXOUT
        IF(ILL(3).EQ.1)     GOTO 7053
        IF(IFILT .NE.1) WRITE(5,1000) I,X1,X2,ELECTR(I),BB(I2)
1000    FORMAT(I5,2(1X,F10.4),10X,2(1X,F12.2))
        IF(IFILT.EQ.1)  WRITE(5,1001) I,X1,X2,ELECTR(I),
     2                  BB(I2),X3
1001    FORMAT(I5,2(1X,F10.4),10X,2(1X,F12.2),16X,F10.4,3X,F12.2)
7053    CONTINUE
           ELECTR(I)=X1
           BB(I2)=X2
           I2=I2 + 1
C*
C*
C*      ADD IN THE FEED FOR CLOCK 1
C*             55 MILLEVOLTS
C*      SUBTRACT THE FEED FOR CLOCK 2
C*               55 MILLEVOLTS
C*
C*
             CLOCK=55.E-3
C+
C+
C+       ADD IN THE DIRECT FEEDTHROUGH
C+       MAXIMUM INPUT VOLTAGE CORRESPONDS
C+       TO 2 MILLEVOLTS AT OUTPUT
C+
C+
100     CONTINUE
        CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
          WRITE(5,8099)  NUMB,AVE,VAR,VAR1
8099      FORMAT(' INPUT ',I6,' AVE ',1PE15.8,' SD ',1PE15.8,1X,1PE15.8/)
             AVE=1.
      IF(ILL(3).EQ.0) CALL PLOT(ELECTR,NUMB,XMIN,XMAX,AVE,AVE,AVE)
           XZ(12)=VMAXO
           XZ(13)=CLOCK
        REWIND 1
        ENDFILE 1
        WRITE(2'IPP) BB
        WRITE(6,8010) IPP
8010    FORMAT(' DONE WITH OUTP'  ,I6//)
             IPP=1
           AVE=0.
           AVE1=0.
           VAR=0.
           VAR1=0.
             NUMBB=NUMB/2 + 1
             I2=31
        DO 8079  I=1,NUMB
        IF(I2.LE.30)  GOTO 8078
             I2=1
        READ(2'IPP)  BB
          IPP=IPP + 1
8078    CONTINUE
        ELECTR(I)=BB(I2)
        I2=I2 + 1
```

```
      AVE=AVE + ELECTR(I)
      X1=ELECTR(I)**2
       VAR=VAR + X1
      IF(I.LT.NUMBB)  GOTO 8079
        AVE1=AVE1 + ELECTR(I)
        VAR1=VAR1 + X1
8079  CONTINUE
        X1=FLOAT(NUMB)
        VAR=X1*VAR - AVE*AVE
        IF(VAR.GT.0.)  VAR=SQRT(VAR/(X1*(X1-1.)))
        AVE=AVE/X1
        X1=FLOAT(NUMB/2)
        VAR1=X1*VAR1 - AVE1*AVE1
        IF(VAR1.GT.0.)  VAR1=SQRT(VAR1/(X1*(X1-1.)))
        AVE1=AVE1/X1
        WRITE(5,8075)  NUMB,AVE,VAR,AVE1,VAR1
8075  FORMAT(' OUTPUT  #',I6,' AVE ',1PE15.8,' SD ',1PE15.8/
     2 ' HALF THE OUTPUT AVE ',1PE15.8,' SD ',1PE15.8//)
      CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
      WRITE(5,8075)  NUMB,AVE,VAR1
        AVE=1.
   IF(ILL(3).EQ.0) CALL PLOT(ELECTR,NUMB,XMIN,XMAX,AVE,AVE,AVE)
        ENDFILE 2
              RETURN
3000  REWIND 1
      GOTO 3001
              END
```

BEST_AVAILABLE COPY

```
C*
C*
C*      LITTLE BOOKKEEPING
C*
C*      CCD26.FTN
C*
C*
C*
              SUBROUTINE SETUP
        REAL ARR(30)
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /CCO/B(1200)
      COMMON /INPUT/A(1200)
            IW=0
        IF(IJ(30).EQ.0)  RETURN
        ICC=1
800     CONTINUE
         NUMB=IJ(25)
           K=0
           NUMBB=NUMB/2 + 1
        DO 110 I=NUMBB,NUMB
           K=K + 1
           A(K)=A(I)
110     CONTINUE
          NUMB=K
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
        WRITE(5,8080) NUMB,AVE,VAR,VAR1
8080    FORMAT(1H1'  #  MEAN  SD  ',I6,4(1X,1PE15.8)/)
        IF(IW.EQ.1)  GOTO 77
          J=1
          IND=2
2       NUM=NUMB/IND
        IF(NUM.EQ.0) GOTO 5
         IND=IND*2
          J=J + 1
          GOTO 2
5       CONTINUE
        IF(NUMB.EQ.(IND/2)) J=J - 1
          IF(IW.EQ.0)  GOTO 6
77      CONTINUE
            CALL WGHT(A,IW,NUMB)
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
6         CONTINUE
            DO 18 I=1,NUMB
             A(I)=A(I) - AVE
18          CONTINUE
          IND=2**J
          IPP=IND - NUMB
        IF(IPP.EQ.0)  GOTO 10
           K=NUMB + 1
        DO 7 I=K,IND
7       A(I)=0.
10      DO 20 I=1,IND
        B(I)=0.
20      CONTINUE
        CALL FRXFM(J,A,B)
          IND=IND/2
        DO 30 I=1,IND
         D=A(I)**2 + B(I)**2
```

BEST AVAILABLE COPY

```
      D=SQRT(D)
     A(I)=D
30   CONTINUE
     CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,IND)
         I=1
     CALL EPLOT(A,XMAX,IND,I,I)
         ICC=ICC + 1
         IW=1
     IF((IPP.EQ.0).AND.(ICC.LT.3)) GOTO 800
       RETURN
       END
```

```
C*
C*
C*      LITTLE BOOKKEEPING
C*
C*      CC027.FTN
C!
C*
C*
              SUBROUTINE FRXFM(N2POW,XT,YT)
C*
C*     DECIMATION IN FREQUENCY FFT ALGORITHM
C*
C*
        DIMENSION XT(2),YT(2)
        N=2**N2POW
        M=N2POW
        DO 600 L0=1,M
          LMX=2**(M-L0)
          LIX=2*LMX
          SCL=6.2831853072/FLOAT(LIX)
         DO 600 LM=1,LMX
           ARG=FLOAT(LM-1)*SCL
           C=COS(ARG)
           S=SIN(ARG)
          DO 600 LI=LIX,N,LIX
           J1=LI-LIX+LM
           J2=J1+LMX
           T1=XT(J1) -XT(J2)
           T2=YT(J1) - YT(J2)
           XT(J1)=XT(J1) + XT(J2)
           YT(J1)=YT(J1) + YT(J2)
           XT(J2)=C*T1 + S*T2
           YT(J2)=C*T2 - S*T1
600     CONTINUE
C*
C*     BIT REVERSAL
C*
         NV2=N/2
         NM1= N -1
         J=1
        DO 635 I=1,NM1
          IF(I.GE.J) GOTO 631
           T1=XT(J)
           T2=YT(J)
           XT(J)=XT(I)
           YT(J)=YT(I)
           XT(I)=T1
           YT(I)=T2
631       K=NV2
620     CONTINUE
           IF(K.GE.J) GOTO 635
           J=J -K
           K=K/2
           GOTO 620
635     J=J+K
             RETURN
             END
```

```
C*
C*
C*    CCD28,FTN
C*
C*
            SUBROUTINE WGHT(A,IW,NUMB)
      REAL A(2)
      COMMON /RAND/PI,PII
C*
C*
C*
        N=NUMB - 1
        IF(NUMB.NE.2*(NUMB/2)) N=NUMB
        N=N/2 - 1
        CONST=PII/FLOAT(NUMB)
        ALPHA=0.54
        IF(IW.EQ.2)  ALPHA=0.5
        C1=1. - ALPHA
        DO 1 I=1,NUMB
          T1=CONST*FLOAT(I+N)
        A(I)=A(I)*(ALPHA + C1*COS(T1))
1       CONTINUE
            RETURN
            END
```

BEST AVAILABLE COPY

```
C*
C*
C*        CCD29.FTN
C*
C*
          SUBROUTINE EPLOT(XT,XMAX,LNUMB,LSTRT,LINT)
C         FOR PLOTTING RESULTS ON A SCALE 0 TO 50 DB
C         ASSUMES THAT CAPTIONING IS PROVIDED, AND POINTS EXIST (UP TO LEND)
C         NORMALIZES POINTS TO XMAX BEFORE PLOTTING
C*
C*
C*    XT VECTOR OF STORED POINTS TO BE PLOTTED
C*    XMAX MAX VALUE IN VECTOR XT
C*    LNUMB NUMBER OF POINTS TO BE PLOTTED
C*    LSTRT INDEX OF FIRST POINT TO BE PLOTTED
C*    LINT INTERVAL BETWEEN PLOTTED POINTS IN ARRAY
C*
C*    OUTPUT OF 999 MEAN THAT POINT WAS LESS THEN
C*     OR EQUAL TO ZERO
C*
C*******M27- LATEST RECENSION DATED::21,APR,77
        REAL AKAR(5)
        REAL XT(2)
        COMMON /CCD/ALINE(101)
          DATA AKAR/'.','.','+',' ','0'/
          LEND=LSTRT+(LNUMB-1)*LINT
          KOUNT=0
          WRITE(5,15)
15        FORMAT(//59X,'DB DOWN'/)
          WRITE(5,17)
17        FORMAT(/1X,'PT # VALUE 100 ',17X,'80',18X,'60',18X,'40',
     1     18X,'20',18X,'0 INDEX')
          DO 20 I=LSTRT,LEND,LINT
          TEST=XT(I)/XMAX
          IF(TEST) 24,24,26
24        DB=999.
          GO TO 30
26        DB=-20.*ALOG10(TEST)
30        IF( MOD(KOUNT,10).NE.0 ) GO TO 50
C          EVERY TENTH LINE
          DO 35 J=1,101
35        ALINE(J)=AKAR(1)
          DO 40 J=1,101,5
40        ALINE(J)=AKAR(3)
          GO TO 70
C          ALL OTHER LINES
50        DO 55 J=1,101
55        ALINE(J)=AKAR(4)
          DO 60 J=1,101,10
60        ALINE(J)=AKAR(2)
C          LINE READY FOR INSERTION OF POINT
70        KOUNT=KOUNT+1
          L=101-IFIX(DB+.5)
          IF(L.LT.1) GO TO 90
          ALINE(L)=AKAR(5)
90        WRITE(5,95) I,DB,(ALINE(J),J=1,101),KOUNT
95        FORMAT(1X,I4,F7.2,1X,101A1,I5)
20        CONTINUE
          WRITE(5,17)
          RETURN
          END
```

```
C*
C*
C*      SUBROUTINE PLOTS OUT AN ARRAY ON LINEPRINTER
C*
C*      CCD16.FTN
C*
C*
C*
        SUBROUTINE PLOT(ARRAY,NELMNT,AMIN,AMAX,CONT,DELT,TINTL)

C       ARRAY IS THE ARRAY OF DATA TO BE PLOTTED FROM THE THE 1ST
C       ELEMENT TO THE ELEMENT NUMBER GIVEN BY NELMNT.
C       AMIN IS THE MINIMUN VALUE THE PLOT COULD REACH.
C       AMAX IS THE MINIMUN VALUE THE PLOT COULD REACH.
C       CONT IS A SWITCH THAT TELLS THE SUBROUTINE IF THE INPUT
C       ARRAY IS A CONTINUATION OF THE LAST PLOT.
C       CONT GREATER THAN 1.0 IMPLIES A CONTINUATION.
C       DELT IS THE INCREMENT TO BE USED ALONG THE ABSCISSA.
C       TINTL IS THE INITIAL VALUE OF THE ABSCISSA.
C
C       ***NOTE***
C
C       TINTL IS CHANGED BY THE SUBROUTINE. IT IS RESET TO THE VALUE
C       THAT IS EXPECTED AS THE INITIAL VALUE OF THE NEXT CALL IF THE
C       CONTINUATION OPTION IS USED.
C       IF THE CONTINUATION OPTION IS USED AND THE INITIAL TIME IS CHANGED
C       FROM THE EXPECTED VALUE, THE OUTPUT WILL BE FLAGED WITH A *.
C       THE TIMING WILL BE RESEQUENCED TO AGREE WITH THE NEW VALUE.
C
        DIMENSION ARRAY(5),XS(5),STRING(123)
        DATA SPACE/' '/,STAR/'O'/,GRID/'+'/
         AVE=0.
         VAR=0.
        TINTL=ABS(TINTL)
        DO 1 I=1,123
1       STRING(I)=SPACE
        DO 2 I=12,112,25
2       STRING(I)=GRID
        IF(CONT-1.)3,3,4
3       X=1.001*(AMAX-AMIN)/120.
C       KR GIVES X ROUNDED TO KR SIGNIFICANT DIGITS EQUALS XIN.
        KR=6
        ZP=-69.0775
        Z=AMAX1(ABS(X),EXP(ZP))
        LOG10F=ALOG(Z)/2.302585
        K1=INT(LOG10F+50.)
        PWRK=10.**(50+KR-K1)
        SIGK=AINT(X*PWRK)
        PWRKM1=10.**(49+KR-K1)
        SIGKM1=AINT(X*PWRKM1)
        Y=10.*SIGKM1
        YP=SIGK-Y
        NY=INT(YP)
        NY=((NY)/5+1)*5
        YP=AINT((NY+Y)/10.)
        ROUNDF=YP/PWRKM1
        XIN=ROUNDF
        XIN=X
        AVE=(AMAX+AMIN)/2.
```

```
      REVAVE=AINT(AVE/XIN)*XIN
      XMIN=REVAVE-60.*XIN
      XS(1)=REVAVE-50.*XIN
      XS(2)=REVAVE-25.*XIN
      XS(3)=REVAVE
      XS(4)=REVAVE+25.*XIN
      XS(5)=REVAVE+50.*XIN
      WRITE(5,1000)DELT,TINTL,XS
1000  FORMAT(/5X24HABSCISSA IS IN UNITS OF 1PE13.7,
     1 ' INITIAL VALUE ',1PE13.7/
     2 61X21H------AMPLITUDE------//2X8HABSCISSA5X
     3 1PE11.4,4(14X1PE11.4)/1X,132(1H_))
C*
C*     BY PASS CODE AFTER GOTO 6
C*
      KNT=1
      IF(TINTL.GT.1.) KNT=TINTL
      IF(KNT.GT.0)  GOTO 6
      TSAVE=TINTL
      KNT=1
4     KNTCHK=(TINTL-TSAVE)/DELT+.1
      IF(KNTCHK-KNT)5,6,5
5     WRITE(5,1001)
1001  FORMAT(/2H */)
      KNT=KNTCHK
6     DO 7 I=1,NELMNT
      AVE=AVE + ARRAY(I)
      VAR=VAR + ARRAY(I)*ARRAY(I)
      K=((ARRAY(I)-XMIN)/XIN+2.5)
      IF(K.GT.122)K=123
      IF(K.LT.1)K=1
      TEMP=STRING(K)
      STRING(K)=STAR
      WRITE(5,1002)KNT,(STRING(J),J=2,123)
1002  FORMAT(I10,1X123A1)
      KNT=KNT + 1
7     STRING(K)=TEMP
      TINTL=FLOAT(KNT)*DELT+TSAVE
      XIN=NELMNT
      XMIN=(XIN - 1.)*XIN
      VAR=XIN*VAR - AVE*AVE
      IF(VAR.GT.0.)  VAR=SQRT(VAR/XMIN)
      AVE=AVE/XIN
      WRITE(5,8000) NELMNT,AMIN,AMAX,AVE,VAR
8000  FORMAT(' # OF ELEMENTS ',I5/
     2' MINIMUM VALUE ',1PE15.8/
     3' MAXIMUM VALUE ',1PE15.8/
     4' MEAN OF ELEMENTS',1PE15.8/
     5' SD OF THE ELEMENTS',1PE15.8//)
      RETURN
      END
```

BEST AVAILABLE COPY

```
C*
C*
C*
C**1     KEY TO CCD STUDY ARRAY BINSTR
C*
C*
      COMMON /BINSTR/XX(30),IJ(30)
C*
C*
C*        IJ(1) # OF STAGES IN CCD
C*        IJ(2) DEBUGGING AID  PRINTS OUT INTERMEDIATE VALUES
C*              NO 0     YES 1
C*        IJ(3) LENGH OF INPUT PULSE
C*        IJ(4) COMPUTE TAPPED DELAY LINE RESPONSE
C*              NO 0      YES 1
C*        IJ(5) FEEDTHROUGH VOLTAGE ADDED N=0 Y=1
C*        IJ(6) SURFACE OR BURIED DEVICE
C*        IJ(7) PLOT OUTPUT AND INPUT Y=0 N=1
C*        IJ(8)  NOISE INJECTED OR NOT  Y=0 N=1
C*        IJ(10) SELECT NOISE SOURCES N=0, Y=1
C*        IJ(11) INPUT NOISE ADDED
C*        IJ(12) SHOT NOISE ADDED
C*        IJ(13) TRANSFER NOISE ADDED
C*        IJ(14) OUTPUT NOISE ADDED
C*        IJ(15) FILTER NOISE ADDED
C*        IJ(16) INTERFACE NOISE ADDED
C*        IJ(17) NON LINEAR INPUT CHARACTERISTIC
C:                YES= 0    NO = 1
C*        IJ(18)  DARK CURRENT NOISE
C*        IJ(20) HOLD SIGNAL FOR ANY TIME Y=0 N=1
C*        IJ(27) # OF ELEMENTS IN FILE ON DAT SLOT 2
C*        IJ(28) # OF SINUSODIAL SIGNALS ADDED AT INPUT
C*        IJ(29) TYPE OF SIGNAL 0 PULSE 1 SIN
C*        IJ(30) FFT OF OUTPUT
C*
C*
C*        XX(1) TRANSFER INEFFICIENCY
C*        XX(2) MEAN VALUE OF THE INITIAL STATE OF DEVICE
C*        XX(3) SD OF INITIAL STATE
C*        XX(4) CLOCK FREQUENCY
C*        XX(6) SD OF INPUT NOISE
C*        XX(7) SD OF SHOT NOISE
C*        XX(8) SD OF TRANSFER NOISE
C*        XX(9) SD OF OUTPUT NOISE
C*        XX(10) INPUT LEVEL OF INPUT PULSE 0 TO 2 VOLTS
C*        XX(11) % ERROR OF THE TAP WEIGHTS
C*        XX(12) MAXIMUM OUTPUT VOLTAGE
C*        XX(13) OUTPUT VOLTAGE OF CLOCK
C*        XX(14) FEEDTHROUGH VOLTAGE LEVEL
C*        XX(15) AREA OF WELL
C*        XX(16) BACKGROUND CHARGE 0 TO 35 %
C*        XX(17) SD OF FILTER NOISE
C*        XX(18) CLOCK SWING VOLTAGE
C*        XX(19) SD OF INTERFACE NOISE
C*        XX(20) MEAN OF INTERFACE NOISE
C*        XX(21) TIME SIGNAL HELD IN DEVICE
C*        XX(22) OUTPUT SAMPLING RATE
C*        XX(23) SHOT NOISE FOR OUTPUT FREQUENCY
C*        XX(24) CONSTANT A FOR DARK CURRENT MULTIPLY
C*        XX(25) NUMBER OF ELECTRONS ADDED FOR DARK CURRENT
C*        XX(26) AMBIENT TEMPERATURE READ IN DEGREES C
C*                     CONVERTED TO KELVIN
C*        XX(27) FREQUENCY OF 4TH INPUT
C*        XX(28) FREQUENCY OF 3TH INPUT
C*        XX(29) FREQUENCY OF 2TH INPUT
```

APPENDIX B. COMPUTER LISTING OF MATCHED LINEAR FM FILTER

```
C
C       CCD1.FTN
C
C
C
C
C           CCD STUDY   MODELING AND SIMULATION OF THE MATCHED FILTER
C
C
C
C****************************************************************
C****************************************************************
C
      REAL A(2),B(3)
      COMMON IW
      COMMON /RAND/G0(10)
      COMMON /BINSTR/G(50)
      COMMON /CCD/G1(1202)
      COMMON /INPUT/G2(1200)
      COMMON /VOLTS/G5(100)
      COMMON /PASS/GG(50)
      COMMON /FILTER/FILT(600)
10     CONTINUE
       WRITE(5,100)
100    FORMAT(1H1'    CCD STUDY    TEST RUN'//)
       CALL TIME(A)
       CALL DATE(B)
       WRITE(5,101) B,A
101    FORMAT(5X,'DATE:   ',3A4,5X,'TIME:   ',2A4//)
       CALL LINK('C0')
       CALL LINK('C1')
         IW=0
30     CONTINUE
       CALL LINK('C2')
       CALL LINK('C3')
       CALL LINK('C4')
       IW=IW + 1
       IF(IW.LT.4)  GOTO 30
       CALL LINK('C5')
       CALL LINK('C6')
C*
C*
C*     THE FOLLOWING CODE IS USED TO FORCE THE
C*       MAIN MODULE TO CARRY THE I/O ROUTINES
C*       SEE DESCRIPTION IN FORTRAN OR LINK
C*       MANUALS
C*
C*
               IDUM=0
      IF(IDUM.EQ.0)  GOTO 10
         READ(1'INDEX) A
         WRITE(1'INDEX) A
         READ(6,1001) II,A
         WRITE(6,1001) II,A
1001     FORMAT(I5,E15.8,F10.0)
          END
```

```
C     CCD6.FTN
C
C
C
C          SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN
C
C
            SUBROUTINE INSTR
        REAL A(3)
      COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
     2          ZL(20),ISTAGE,IPRINT,ILENGT,IFILT,NRVS,IJ(20)
      COMMON /BINSTR/XXZ(30),IJL(30)
      COMMON /VOLTS/WW1,WW2,ITIME
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      COMMON /RAND/R1(4),RR(6)
         DATA A/4HTEMP,4H02.D,4HAT00/
           IJL(21)=0
           IRW(3)=0
           IJL(9)=9998
        WRITE(6,7000)
7000    FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/)
        READ(6,91) I
        IF(I.NE.0) GOTO 7005
        WRITE(6,7001)
7001    FORMAT(' NAME OF FILE XXXXXX.D '/)
        READ(6,7002) A(1),A(2)
7002    FORMAT(2A4)
7005    WRITE(5,7003) A
7003    FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
        CALL SETFIL(2,A,IER2,'DK',0)
        DEFINE FILE 2(200,64,U,IVAR)
1       WRITE(6,100)
100     FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)'//)
        READ(6,101) X
101     FORMAT(F10.0)
             IUPPER=600
             ILOWER=0
             ISTAGE=X
        IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER))  GOTO 3
          WRITE(6,201) ISTAGE,ILOWER,IUPPER
201     FORMAT(' ERROR MESSAGE  # OF STAGES TO SMALL OR TO LARGE'/
     2' # OF STAGES:  ',I4,'  LOWER LIMIT:  ',I4,' UPPER:  ',I4//)
             GOTO 1
3       WRITE(6,103)
103     FORMAT(' SD OF THE INITIAL STATE (F10.0) '/
     2' IF < 0 THEN NO BACKGROUND VOLTAGE ADDED '/)
        READ(6,101) XSD
C*
C*
        WRITE(6,5123)
5123    FORMAT(' NOISE + TARGET 0'/
     2          ' NOISE          1'/
     3          ' TARGET         2'/)
        READ(6,91)    IJL(28)
C*
        XXZ(3)=XSD
        IJL(1)=ISTAGE
4       WRITE(6,104)
104     FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1.)'/)
        READ(6,91)    IJ(1)
        IJL(6)=IJ(1)
        IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
        WRITE(6,108)
```

```
108     FORMAT(' AREA OF WELL IN MIL**2 '/)
        READ(6,101) ZL(5)
        WRITE(6,107)
107     FORMAT(' % OF BACKGROUND CHARGE '/
     2  ' <0 THEN SPECIFY TRANSFER LOST '/)
        READ(6,101) ZL(6)
        IF(ZL(6).LT.0.) WRITE(6,7891)
7891    FORMAT(' FRACTION LOST EACH TIME .XXXX'/)
        IF(ZL(6).LT.0.) READ(6,101)  XPERC
        IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,IJ)
        WRITE(6,109)
109     FORMAT(' CLOCK SWING VOLTAGE '/)
        READ(6,101) ZL(8)
        XXZ(1)=XPERC
        XXZ(15)=ZL(5)
        XXZ(16)=ZL(6)
        XXZ(18)=ZL(8)
        WRITE(6,9050)
9050    FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 '/)
        READ(5,91) IJL(7)
        WRITE(6,8151)
8151    FORMAT(' HAMMING WEIGHTING TO OUTPUT Y=0 N=1'/)
        READ(6,91) IJL(4)
        WRITE(6,7011)
7011    FORMAT(' FFT OF OUTPUT  Y=1 N=0 '/)
        READ(6,91) IJL(30)
5       WRITE(5,1000) ISTAGE,XPERC,ZL(6),ZL(5)
1000    FORMAT(' # OF STAGES IN THE CCD ',I5/
     3' CTI OF DEVICE ',1PE15.8/
     4' % OF THE BACKGROUND CHARGE ',1PE15.8/
     4' AREA OF THE WELL (MIL**2)',1PE15.8//)
6       WRITE(6,206)
206     FORMAT(' CLOCK FREQUENCY (F10) '/)
           CLCKMX=1.E10
        READ(6,101) FCLOCK
      IF((FCLOCK.GT.0.).AND.(FCLOCK.LE.CLCKMX)) GOTO 60
        WRITE(6,1006) CLCKMX
1006    FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO 'F10.0/)
              GOTO 6
60      CONTINUE
        WRITE(5,701)  FCLOCK
701     FORMAT('   CLOCK RATE  ',1PE15.8/)
80      WRITE(6,800)
800     FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 '/)
        READ(6,101) ZZ1
          ITIME=ZZ1
        IF((ITIME.LT.0).OR.(ITIME.GT.1200))   GOTO 80
        WRITE(6,90)
90      FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1'/)
        READ(6,91) IPRINT
91      FORMAT(I1)
        WRITE(6,9008)
9008    FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1'/)
C*
C*      MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
C*
C*
        XXZ(4)=FCLOCK
        IJL(2)=IPRINT
             XMAXV=2.8
             WW1=XMAXV
        READ(6,91)     NRVS
96      WRITE(6,93)
93      FORMAT(' DURATION OF THE SIGNAL MIN=0 MAX=1200'/)
        READ(6,101) ZZ1
        ILENGT=771
```

```
      WRITE(6,7024)
7024  FORMAT(' BANDWIDTH OF THE LINEAR FM (HERTZ) '/)
      READ(6,101)   XXZ(30)
        XXZ(8)=XXZ(30)/XXZ(4)
      WRITE(6,8025)
8025  FORMAT(' SIGNAL TO NOISE RATIO AT IF(DB) '/)
      READ(6,101)  XXZ(29)
      WRITE(6,7028)
7028  FORMAT(' PHASE ANGLE OF TARGET DEGREES '/)
      READ(6,101) XXZ(28)
      WRITE(5,7030)  XXZ(30),XXZ(29),XXZ(28)
7030  FORMAT(' BANDWIDTH OF SIGNAL '1PE15.8/
     2 ' SIGNAL TO NOISE OF SIGNAL(DB) '1PE15.8/
     3 ' PHASE ANGLE OF THE SIGNAL      '1PE15.8//)
      WRITE(6,8053)
8053  FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 '/)
      READ(6,101) XXZ(5)
       XXZ(5)=WW1*XXZ(5)/100.
95    CONTINUE
      IJL(3)=ILENGT
      IJL(5)=NRVS
      WRITE(6,8010)
8010  FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1'/)
      READ(6,91) IJ(12)
      WRITE(6,97)
97    FORMAT(' MEAN ERROR IN TAP WEIGHTS '/)
      READ(6,101) XXZ(20)
      WRITE(6,7128)
7128  FORMAT(' SD OF THE TAP ERROR (.0061 .07)'/)
      READ(6,101) XXZ(17)
      IJL(20)=1
      WRITE(6,9034)
      READ(6,101) ZZ1
      XXZ(26)=ZZ1 + 273.
      WRITE(5,9035) ZZ1,XXZ(26)
      WRITE(6,9033)
9033  FORMAT('  DARK CURRENT ADDED Y=0 N=1 '/)
      READ(6,91) IJ(13)
      IF(IJ(13).EQ.1)  GOTO 9036
9034  FORMAT(' AMBIENT TEMPERATURE DEGREES C '/)
9035  FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,'  (K) ',F10.4/)
9036  CONTINUE
      IJL(17)=IJ(12)
      IJL(18)=IJ(13)
      WRITE(6,6011)
6011  FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10'/)
      READ(6,91)  IJL(19)
      IF(IJL(19).EQ.0)  GOTO 8000
      WRITE(6,6012)
6012  FORMAT(' WHICH INPUT IS TO BE CHANGED '/
     2 ' 1= # OF STAGES, 2=SD OF THE TAP WEIGHTS '/
     3 ' 3= AREA OF WELL, 4=BACKGROUND CHARGE '/
     4 ' 5=CLOCK FREQUENCY,6=AMBIENT TEMPERATURE '//)
      READ(6,91) IJL(22)
       K=IJL(19)
      DO 6019 I=1,K
       WRITE(6,6013) I
6013  FORMAT(' INPUT THE ',I6,' VALUE '/)
       READ(6,101) RR(I)
6019  CONTINUE
        WRITE(5,6015) (I,RR(I),I=1,K)
6015  FORMAT(' MULTIPLE RUNS '//7(1X,I2,2X,1PE15.8))
        WRITE(6,8717)
8717  FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 '/)
      READ(6,91) IRW(1)
      IF(IRW(1).EQ.0)  GOTO 8000
```

```
      WRITE(6,6012)
      READ(6,91) IRW(2)
      K=IRW(1)
      DO 8718 I=1,K
      WRITE(6,6013) I
      READ(6,101)  ROW(I)
8718  CONTINUE
      WRITE(5,6015)  (I,ROW(I),I=1,K)
8000  WRITE(6,8001)
8001  FORMAT(' RUN WITH NOISE Y=0 N=1 '/)
      READ(6,91) IJ(3)
      IJL(8)=IJ(3)
      IF((IJ(3).LT.0).OR.(IJ(3).GT.1))  GOTO 8000
      IF(IJ(3).EQ.1)   RETURN
        K=10
      DO 9000 I=5,11
       IJ(I)=0
       IJL(K)=0
        K=K + 1
9000  CONTINUE
      WRITE(6,8003)
8003  FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1'/)
      READ(6,91) IJ(5)
      IJL(10)=IJ(5)
      IF(IJ(5).EQ.0)  RETURN
      WRITE(6,8004)
8004  FORMAT(' ADD IN INPUT NOISE Y=0 N=1 '/)
      READ(6,91) IJ(6)
      WRITE(6,8005)
8005  FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1'/)
      READ(6,91) IJ(7)
      WRITE(6,8006)
8006  FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1'/)
      READ(6,91) IJ(8)
      WRITE(6,8007)
8007  FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1'/)
      READ(6,91) IJ(9)
      WRITE(6,8008)
8008  FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1'/)
      READ(6,91) IJ(10)
      WRITE(6,8009)
8009  FORMAT(' ADD IN INTERFACE NOISE '/)
      READ(6,91) IJ(11)
        K=11
      DO 57 I=6,11
      IJL(K)=IJ(I)
      K=K + 1
57    CONTINUE
              RETURN
              END
C*
C*
C*      C1 LINK STRUCTURE
C*
C*
C*  C1,C1<CCD,STB,C1,CCD5,FTNLIB/L/U/E
C*
     COMMON /RAND/PI,PII
     COMMON /VOLTS/Q1,Q2,ITIM,IPP
          PI=4.*ATAN(1.)
          PII=2.*PI
        CALL PRTVAL
         IPP=1
        CALL RETURN
          END
```

```
C*
C*      CCDS.FTN
C*
C*
C*      SUBROUTINE PRINTS OUT MEANS AND SD OF THE
C*          VARIOUS NOISE RANDOM VARIABLES
C*
C*
                SUBROUTINE PRTVAL
      REAL JD,NSS
      COMMON IBIT
      COMMON /BINSTR/XX(30),IJL(30)
      COMMON /RAND/PI,PII,II1,II2
      COMMON /PASS/STAD(20)
C*
C*
C*          NOISE ADDED OR NOT
C*
            INOISE=IJL(8)
            IDARK=IJL(18)
C*
C*
C*    CONSTANTS NEED IN CALCULATIONS
C*
C*
C*
        XKB=8.617E-5
        AREA=XX(15)*6.4516E-6
        Q=1.602E-19
        NSS=1.E10
        C=1.E-13
        QQ=1.6498E-24
        TD=100.E-6
        XD=1.E-4
        SIGMA=1.E-15
        VTH=8.25
        XNST=5.E9
        XNNN=5.E14
        XLN=0.05609
        TEMP=XX(26)
        FCLOCK=XX(4)
C*
C*
C*   INPUT NOISE
C*
C*    MEAN=0
C*
C*     VAR= XKB*TEMP*C/Q**2
C*
C*
C*
        X=XKB*TEMP
        XX(6)=SQRT(2.*X*C/(3.*Q))
C*
C*
C*      OUTPUT NOISE
C*
C*   SAME AS ABOVE
C*
C*
        XX(9)=XX(6)
C*
C*
```

```
C*
C*     FAST INTERFACE
C*
C*
C*
C        MEAN=0
C        SD=SQRT(0.7*K*TEMP*NSS*AREA)
C
C
         XX(19)=SQRT(0.7*X*NSS*AREA)
C*
C*
C*
C*       DARK CURRENT
C*
C*
         IF(XX(26).LT.250.)  GOTO 50
           XNI=1.21/(8.617E-5*TEMP)
           XNI=EXP(-XNI)
           XNI=XNI*1.5E33
           XNI=XNI*TEMP**3
           XNI=SQRT(XNI)
             GOTO 51
50       CONTINUE
           XNI=53228827.58
51       CONTINUE
           GBI=XNI*XNI*XLN/(XNNN*TD)
           GSI=0.5*XNI*SIGMA*VTH
           GDI=XNI*XD/(2.*TD)
           XX(25)=10000.
           STAD(20)=GBI
           STAD(19)=GSI
           STAD(18)=GDI
           STAD(17)=AREA/FCLOCK
           XX(24)=AREA
           STAD(16)=XNST
           STAD(15)=QQ/1.0363E-5
         IF(IDARK.EQ.1) XX(25)=0.
         IF(IDARK.EQ.0) WRITE(5,8010) GBI,GSI,GDI,TOTALI
8010     FORMAT(' INDIVIDUAL SOURCES OF DARK CURRENT '/
     2    6(3X,1PE15.8))
C*
C*       SHOT NOISE
C*
C*      MEAN=0.
C*
C*      SD= SQRT(JD*AREA/Q*FCLOCK)
C*
C*
         JD=GBI + GSI*XNST + GDI
         JD=JD*STAD(15)
         XX(7)=SQRT(JD*AREA/(Q*FCLOCK))
C*
C*       PRINT OUT THE MEANS AND SD
C*
C*
         IF(INOISE.EQ.1)  RETURN
         IF(IBIT.GT.0) RETURN
         WRITE(5,9088)  XX(25)
9088     FORMAT(' DARK CURRENT ELECTRONS ADDED PER
     2 'TRANSFER ',1PE15.8//)
C*
           Z=0.
         WRITE(5,2) Z,XX(6)
         WRITE(5,3) Z,XX(7)
```

```
      WRITE(5,6) XX(20),XX(17)
      WRITE(5,10) Z,XX(19)
      WRITE(5,7) (IJL(I),I=10,16)
7     FORMAT(' STATUS OF THE NOISE SOURCES'//
     2' SELECT THE NOISE INPUTS Y=1 N=0 ',I2/
     3' ADD IN INPUT NOISE Y=0  N=1 ',I2/
     4' ADD IN SHOT NOISE Y=0 N=1 ',I2/
     5' ADD IN TRANSFER NOISE  Y=0 N=1 ',I2/
     6' ADD IN OUTPUT NOISE Y=0 N=1 ',I2/
     7' ADD IN FILTER NOISE Y=0  N=1 ',I2/
     8' ADD IN INTERFACE NOISE Y=0 N=1 ',I2//)
2     FORMAT(' MEAN OF THE INPUT NOISE    ',1PE15.8,
     2 '    SD  ',1PE15.8/)
3     FORMAT(' MEAN OF THE SHOT NOISE     ',1PE15.8,
     2 '    SD  ',1PE15.8/)
4     FORMAT(' MEAN OF THE TRANSFER NOISE ',1PE15.8,
     2 '    SD  ',1PE15.8/)
5     FORMAT(' MEAN OF THE OUTPUT NOISE   ',1PE15.8,
     2 '    SD  ',1PE15.8/)
6     FORMAT(' MEAN OF THE FILTER ERROR    ',1PE15.8,
     2 '    SD  ',1PE15.8/)
10    FORMAT(' MEAN OF THE INTERFACE NOISE  ',1PE15.8,
     2         ' SD   ',1PE15.8/)
            RETURN
            END

C*
C*
C*     C2.FTN
C*
C*     C2 LINK STRUCTURE
C*C
C*
C*  C2,C2<FILT.STB,C2,MOD4,CCD2,FTNLIB/L/U/E
C*
C*
C*
      COMMON IW
      CALL SIGNAL
      CALL INPUT
      CALL RETURN
      END
```

BEST_AVAILABLE_COPY

```
C*
C*
C*
C*       MOD4.FTN
C*
C*
C*      COMBINES SIGNAL PLUS THE NOISE
C*
C*
C*
              SUBROUTINE SIGNAL
      COMMON IW
      COMMON /FILTER/A(30)
      COMMON /INPUT/ARRAY(1200)
      COMMON /VOLTS/WW1,WW2,ITIME,IPP
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /RAND/PI,PII
        WRITE(6,8000)
8000    FORMAT('         SIGNAL'//)
           NSIGNL=IJ(28)
           ASI=SQRT(2.*10.**(XX(29)/10.))
C
C*    PLACE THE TARGET IN THE MIDDLE OF THE SAMPLES
C*       FROM - THE LENGTH OF THE SIGNAL PULSE
C*       TO   + THE LENGTH OF THE SIGNAL PULSE
C*
C
          ISTART=ITIME/2 - IJ(3)/2 + 1
          JEND=ISTART + IJ(3) - 1
C
C*    BANDWIDTH OF THE LINEAR FM  BW=XX(30)
C
         BW=XX(30)
C
C        PHASE IS AN INPUT PARAMETER
C
         PHASE=XX(28)
         RADS=PHASE*PI/180.
C
C    SAMPLING FREQUENCY
C
         FS=XX(4)
         TS=1./FS
        TIMEPL=FLOAT(IJ(3))*TS
        SLOPE=BW*PII/TIMEPL
        SLOPE=SLOPE/2.
        XX(27)=SLOPE
        TIME=-FLOAT(ITIME/2)*TS
        JJ=1
          J=0
            IF(NSIGNL.EQ.2)  GOTO 5
1     READ(1,END=9000,ERR=9000)A
        J=0
5       IF(NSIGNL.NE.2) J=J + 1
      IF(JJ.GT.ITIME)  GOTO 20
       IF(J.GT.30)   GOTO 1
       XSING=0.
       IF(JJ.LT.ISTART)   GOTO 10
        IF(JJ.GT.JEND)  GOTO 10
        ARG=SLOPE*TIME**2 + RADS
        IF(IW.GT.1)  XSING=ASI*SIN(ARG)
        [illegible]  XSING=ASI*COS(ARG)
```

```
      IF(NSIGNL.EQ.0) ARRAY(JJ)=XSING + A(J)
      IF(NSIGNL.EQ.1) ARRAY(JJ)=A(J)
      IF(NSIGNL.EQ.2) ARRAY(JJ)= XSING
      JJ=JJ + 1
      TIME=TIME + TS
         GOTO 5
20    CONTINUE
         RETURN
9000  REWIND 1
      GOTO 1
         END
```

```
C
C     CCD2.FTN
C
C
C
C
C          SUBROUTINE GENERATES THE INPUT SIGNAL TO THE CCD
C
C
C          ASSUMES THAT MAXIMUM VOLTAGE IS 2 VOLTS (XMAXV)
C          WHICH CORRESPONDS TO 100000 ELECTRONS (XMAXEL)
C
C          ITIME IS THE CCD RUN TIME
C
                      SUBROUTINE INPUT
        REAL A(30)
      COMMON IBIT
      COMMON /INPUT/ELECTR(1200)
      COMMON /BINSTR/XZ(30),IJ(30)
      COMMON /VOLTS/XMAXV,XMAXEL,ITIME
      COMMON /CCD/HOLD(1200)
      COMMON /RAND/PI,PII
      COMMON /PASS/STAD(20)
C
C
C       TRIAL RUN   IMPULSE AT TIME  ZERO
C
C
C*
C*     02/18/77 CHANGE IN FULL WELL ELECTRON COUNT
C*
C*      CLOCK SWING
C*
        CS=XZ(18)
        AREA=XZ(15)
        COUL=2.625E-13
        ELECR=6.281E+18
        XMAXEL=AREA*COUL*ELECR*CS
        IF(IJ(6).EQ.1) XMAXEL=XMAXEL/2.
             XZ(2)=XZ(16)*XMAXEL/100.
           IF(XZ(2).LT.0.)  XZ(2)=0.
        IF(IBIT.GT.0)  GOTO 8181
        WRITE(5,1000) XMAXV,XMAXEL,CS,IJ(6)
1000  FORMAT(' MAXIMUM INPUT VOLTAGE ',1PE15.8,
     25X,'CORRESPONDS TO MAXIMUM NO. OF ELECTRONS ',1PE15.8/
     31X,'CLOCK SWING VOLTAGE ',1PE15.8/
     4' SURFACE(FAT ZERO) 0   OR BURIED(SLIM ZERO) 1 ',I2//)
        WRITE(5,2000) IJ(3),XZ(5)
2000    FORMAT(' LENGTH OF THE SIGNAL ',I6/
     3' BIAS VOLTAGE ADDED TO INPUT ',F10.4/)
8181       CONTINUE
             CONST=XMAXEL/XMAXV
             AVE=XZ(2)
             SD=XZ(3)
            BIAS=XZ(5)
             BIAS=BIAS*CONST
             K=31
        IF(AVE.GT.BIAS)  BIAS=AVE
        DO 4 I=1,ITIME
        ELECTR(I)=ELECTR(I)*CONST + BIAS
             K=K + 1
         IF(BIAS.LE.0.)  GOTO 4
        IF(ELECTR(I).GT.XMAXEL)  ELECTR(I)=XMAXEL
```

```
      IF(ELECTR(I).LT.0.) ELECTR(I)=0.
4     CONTINUE
          STAD(5)=BIAS
           RETURN
        END

C*
C*
C*
C*     C3.FTN
C*
C*
C*
C*  C3,C3<FILT.STB,C3,CCD3,FTNLIB/L/U/E
C*
C*
C*
      COMMON IW
      CALL INITL
      CALL RETURN
      END
```

```
C
C
C       CCD3.FTN
C
C
C
C          SUBROUTINE INITIALIZES CCD FOR INPUT DATA
C
C
C
                SUBROUTINE INITL
        REAL AA(30)
      COMMON IBIT
      COMMON /CCD/CCDW(2,601)
      COMMON /BINSTR/XJ(30),IJ(30)
      COMMON /VOLTS/XMAXV,XMAXE
      COMMON /PASS/STAD(20)
               CONST=XMAXE/XMAXV
              ISTAGE=IJ(1)
              IPRINT=IJ(2)
              INOISE=IJ(8)
                BIAS=STAD(5)
        SD=XJ(3)
        IF((SD.LT.0.).AND.(XJ(5).LE.0.)) GOTO 100
        IF(IBIT.EQ.0) WRITE(5,505) AVE,SD,BIAS
505     FORMAT('  MEAN VALUE OF THE INITIAL STATES ',1PE15.8/
     2  ' SD OF THE INITIAL STATES ',1PE15.8/
     3  ' NUMBER OF ELECTRONS ADDED ',1PE15.8/)
                I=1
                 K=1
        IF(SD.LE.0.)  GOTO 2
1       READ(1,END=8000,ERR=8000) AA
                K=1
2               CONTINUE
           CCDW(2,I)=BIAS
        IF(SD.LE.0.) GOTO 5
          CCDW(2,I)=CCDW(2,I) + AA(K)*SD
             K=K + 1
5       CONTINUE
           RES=CCDW(2,I)*XJ(1)
           CCDW(1,I)=RES
           CCDW(2,I)=RES
                I=I + 1
        IF(I.GT.ISTAGE)  GOTO 3
        IF(K.GT.30)      GOTO 1
                GOTO 2
3         CONTINUE
        IF(IPRINT.NE.1) RETURN
        WRITE(5,1000) (I,I=1,ISTAGE)
1000    FORMAT(15X,'STAGES  '/(13I10))
        WRITE(5,1001) (CCDW(1,I),CCDW(2,I),I=1,ISTAGE)
1001    FORMAT(12(1X,F10.2))
                RETURN
100     DO 110 I=1,ISTAGE
          CCDW(1,I)=0.
          CCDW(2,I)=0.
110     CONTINUE
200     WRITE(5,201)
201     FORMAT(' NO BACKGROUND VOLTAGE ADDED '/)
        RETURN
7000       CONTINUE
        BIAS=STAD(5)
        RES=BIAS*XJ(1)
```

```
      BIAS=BIAS - RES
      DO 7001  I=1,ISTAGE
        CCDW(1,I)=RES
        CCDW(2,I)=RES
7001  CONTINUE
        WRITE(5,7010)  RES,BIAS
7010  FORMAT(" BIAS TERMS ADDED TO WELLS ",2(2X,1PE15.8)/)
        RETURN
8000  REWIND 1
        GOTO 1
            END


C*
C*
C*        C4 LINK STRUCTURE
C*
C*
C*    C4,C4<CCD.STB,C4,CCD7,CCD17,CCD18,CCD20,CCD30,FTNLIB/L/U/E
C*
      COMMON IW
      COMMON /VOLTS/Q1,Q2,ITIME,IPP
      IF(IPP.EQ.1)  CALL SD
       CALL XRUN
       CALL RETURN
         END
```

```
C*
C*      CCD7.FTN
C*
C
C
C         SUBROUTINE DOES THE BOOKKEEPING FOR THE CCD2 ARRAY
C               VERSUS TIME
C
C
                SUBROUTINE XRUN
        REAL A(30),B(30)
      COMMON IBIT
      COMMON /VOLTS/Q1,Q2,ITIM
      COMMON /CCD/CCDW(2,601)
      COMMON /INPUT/ELECTR(1200)
      COMMON /BINSTR/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(25),ISTAGE
     2           ,IPRINT,ILENGT,IFILT,ILJ(3),INOISE,IJJ(20)
      COMMON /PASS/STAD(20),ISTAD(20),IVAR
                LL=ISTAGE + 1
C*
C*      SHOT NOISE
C*      INPUT NOISE
C*      TRANSFER NOISE  CHANGED  03/23/77
C*      INTERFACE NOISE ADDED 03/24/77
C*
C*
        ISTART=1
             I3=0
             I4=0
             IJJ(17)=0
          DARK=XZ(20)
        IF(DARK.EQ.0.)  GOTO 5000
             I3=31
          GBI=STAD(20)
          GSI=STAD(19)
          GDI=STAD(18)
          GG=GBI + GDI
          CONST=STAD(17)
          XNST=STAD(16)
            CUR=STAD(15)
           G1=CUR*GBI
           G2=CUR*GSI
           G3=CUR*GDI
5000    CONTINUE
        IF(INOISE.EQ.1)  GOTO 8000
             SDINPT=STAD(1)
             SDMIDL=STAD(2)
             SDTRAN=SQRT(2.*XPERC)
             INPT=ISTAD(1)
             IMIDL=ISTAD(2)
                I3=31
8000    CONTINUE
        CALL COEFFS
           ILL=ITIM
            ITIME=ITIM
             IEND=1
             IREGIN=0
2329    CONTINUE
        DO 1 I=ISTART,ITIME
          IF(I.EQ.1)  GOTO 7002
           IBEGIN=I - 1
            IEND=I - ILL
          IF(IBEGIN.GT.ISTAGE)  IBEGIN=ISTAGE
```

BEST AVAILABLE COPY

```
          IF(IEND.GT.ISTAGE)  IEND=ISTAGE
          IF(IEND.LE.0)  IEND=1
                      CCDW(1,LL)=0.
          J=IBEGIN
         IF(IPRINT .NE.1)  GOTO 25
          WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
1001     FORMAT(I4,(6(1X,E15.8)))
25        CONTINUE
          DO 2 K=1,ISTAGE
              JJ=J + 1
C*
C*       FIND RESIDUE AT CLOCK PULSE 2 IN EACH WELL
C*       TRANSFER REMAINING CHARGE TO WELL AT CLOCK 1
C*       LEAVE RESIDUE IN OLD WELL AT CLOCK 2
C*
C*
              RES=XPERC*CCDW(2,J)
              CCDW(1,JJ)=CCDW(1,JJ) + CCDW(2,J) - RES
          IF(DARK.EQ.0.)  GOTO 5010
          IF(I3.LE.29)  GOTO 5001
            I3=1
3001     CONTINUE
          READ(1,END=3000,ERR=3000) A
5001      CONTINUE
          RAY=SQRT(A(I3)**2 + A(I3 + 1)**2)
          RAYY=XNST*RAY
          RAY=RAYY*G2
         DARKK=CONST*(GSI*RAYY + GG)
          CCDW(1,JJ)=CCDW(1,JJ) + DARKK
              GSUM=RAY + G1 + G3
         IF(IBIT.GT.0)  GOTO 8181
         IF(I.LT.3)  WRITE(5,5002)  I,G1,RAY,G3,GSUM
5002     FORMAT(' CURRENT DENSITIES ',I6,6(1X,E15.8))
         IF(I.LT.6) WRITE(5,5003)  I,DARKK
5003     FORMAT(' ELECTRONS ADDED PER CLOCK ',I6,1X,E15.8)
8181     CONTINUE
           I3=I3 + 2
5010     CONTINUE
              IF(IJJ(5).EQ.0) XRES=CCDW(2,J)
              CCDW(2,J)=RES
         IF(INOISE.EQ.1)  GOTO 8001
           IF(IMIDL.EQ.0)  GOTO 8001
C*
C*       ADD IN NOISE SOURCES OF MIDDLE REGION
C*         SHOT INTERACE*2
C*
               IF(I3.LE.30)  GOTO 10
                  I3=1
3011     CONTINUE
                READ(1,END=3010,ERR=3010) A
10             CONTINUE
           CCDW(1,JJ)=CCDW(1,JJ) + A(I3)*SDMIDL
                I3=I3 + 1
8001     CONTINUE
C*
C*       TRANSFER NOISE ADDED IN ONE PER TRANSFER
C*
         IF(INOISE.EQ.1)  GOTO 8005
         IF(IJJ(5).EQ.1)  GOTO 8005
               IF(I3.LE.30)  GOTO 11
                  I3=1
3021     CONTINUE
                READ(1,END=3020,ERR=3020) A
11              CONTINUE
              RES=XRES
         IF(RES.LT.0.)  RES=-RES
```

```
         XRES=SQRT(RES)*SDTRAN*A(I3)
              I3=I3 + 1
        CCDW(2,JJ)=CCDW(2,JJ) + XRES
        CCDW(1,JJ)=CCDW(1,JJ) - XRES
8005     CONTINUE
       IF(CCDW(1,JJ).GT.Q2)   CCDW(1,JJ)=Q2
       IF(CCDW(2,JJ).GT.Q2)    CCDW(2,JJ)=Q2
         IF(J.LE.IEND)  GOTO 7001
         J=J - 1
2        CONTINUE
7001    CONTINUE
7002     CONTINUE
        IF(I.GT.ILL)  GOTO 21
          CCDW(1,1)=CCDW(1,1) + ELECTR(I)
       IF(INOISE.EQ.1)  GOTO 8002
           IF(INPT.EQ.0)  GOTO 8002
C*
C*      ADD IN INPUT NOISE SOURCES
C*        SHOT INPUT INTERFACE
C*
C*
              IF(I3.LE.30)  GOTO 20
                I3=1
3031    CONTINUE
              READ(1,END=3030,ERR=3030) A
20            CONTINUE
         CCDW(1,1)=CCDW(1,1) + A(I3)*SDINPT
              I3=I3 + 1
8002    CONTINUE
        IF(CCDW(1,1).GT.Q2) CCDW(1,1)=Q2
       IF(IPRINT.NE.1) GOTO 21
       WRITE(5,1001) I,(CCDW(1,JJ),CCDW(2,JJ),JJ=1,LL)
21      CONTINUE
             J=I
        IF(IBEGIN.GE.ILL) IEND=IEND + 1
        IF(J.GT.ISTAGE) J=ISTAGE
         DO 3 K=1,ISTAGE
C*
C*
C*      FIND RESIDUE AT CLOCK 1 WELLS
C*      TRANSFER REMAINING TO CLOCK 2 WELLS
C:      LEAVE THE RESIDUE IN CLOCK 1 WELL
C*
C*
          RES=XPERC*CCDW(1,J)
          CCDW(2,J)=CCDW(2,J) + CCDW(1,J) - RES
          IF(IJJ(5).EQ.0) XRES=CCDW(1,J)
           CCDW(1,J)=RES
        IF(DARK,EQ,0,)  GOTO 5020
        IF(I3.LE.29)  GOTO 5021
         I3=1
3041    CONTINUE
         READ(1,END=3040,ERR=3040) A
5021     CONTINUE
          RAY=SQRT(A(I3)**2 + A(I3+1)**2)
          RAYY=RAY*XNST
          DARK=CONST*(GSI*RAYY + GG)
          CCDW(2,J)=CCDW(2,J) + DARK
            I3=I3 + 2
5020     CONTINUE
       IF(INOISE.EQ.1)  GOTO 8003
          IF(IMIDL.EQ.0)  GOTO 8003
C*
C*      ADD IN MIDDLE NOISE SOURCES
C*      SHOT 2*INTERFACE
C:
```

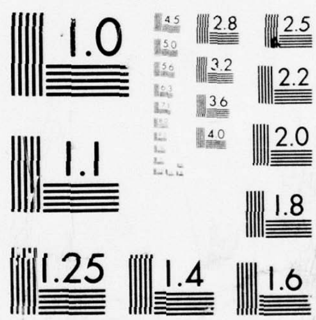
```
C*
             IF(I3.LE.30)  GOTO 30
              I3=1
3051    CONTINUE
              READ(1,END=3050,ERR=3050) A
30           CONTINUE
        CCDW(2,J)=CCDW(2,J) + A(I3)*SDMIDL
              I3=I3 + 1
8003    CONTINUE
C*
C*      ADD IN TRANSFER NOISE
C*
            IF(INOISE.EQ.1)   GOTO 8006
            IF(IJJ(5).EQ.1)   GOTO 8006
             IF(I3.LE.30)  GOTO 35
              I3=1
3061    CONTINUE
              READ(1,END=3060,ERR=3060) A
35           CONTINUE
              RES=XRES
            IF(RES.LT.0.)  RES=-RES
            XRES=SDTRAN*SQRT(RES)*A(I3)
              I3=I3 + 1
            CCDW(2,J)=CCDW(2,J) - XRES
            CCDW(1,J)=CCDW(1,J) + XRES
8006    CONTINUE
        IF(CCDW(1,J).GT.Q2) CCDW(1,J)=Q2
        IF(CCDW(2,J).GT.Q2) CCDW(2,J)=Q2
          IF(J.LE.IEND)  GOTO 99
              J=J -1
3         CONTINUE
99      CONTINUE
        IF(IPRINT.NE.1) GOTO 22
          WRITE(5,1000)    (CCDW(1,J),CCDW(2,J),J=1,ISTAGE)
1000    FORMAT(6(2X,E15.8))
22      CONTINUE
1056    CONTINUE
        CALL FILTER(I,IEND)
1       CONTINUE
                RETURN
3000    REWIND 1
        GOTO 3001
3010    REWIND 1
        GOTO 3011
3020    REWIND 1
        GOTO 3021
3030    REWIND 1
        GOTO 3031
3040    REWIND 1
        GOTO 3041
3050    REWIND 1
        GOTO 3051
3060    REWIND 1
        GOTO 3061
                END
```

```
C*
C*
C*      CCD17.FTN
C*
C*      SUBROUTINE LOADS UP THE WEIGTHS FOR A FILTER
C*
C*
            SUBROUTINE COEFFS
       COMMON IW
       COMMON /FILTER/COEFF(600)
       COMMON /VOLTS/Q1,Q2,ITIME,IPP,B(30),I2
      COMMON /BINSTR/ZL(30),IJ(30)
      COMMON /RAND/PI,PII
            I2=1
          ISTAGE=IJ(1)
          TS=1./ZL(4)
           TIME=-FLOAT(ITIME/2)*TS
           ISTART=ITIME/2 - IJ(3)/2 + 1
              JJ=1
        DO 8080 I=1,ITIME
          IF(JJ.GE.ISTART)  GOTO 8081
             JJ=JJ + 1
             TIME=TIME + TS
8080    CONTINUE
8081       CONTINUE
           SLOPE=ZL(27)
        DO 1 I=1,ISTAGE
             ARGG=SLOPE*TIME**2
        IF((IW.EQ.0).OR.(IW.EQ.2))  COEFF(I)=COS(ARGG)
        IF((IW.EQ.1).OR.(IW.EQ.3))  COEFF(I)=SIN(ARGG)
         TIME=TIME + TS
1       CONTINUE
        IF(IJ(4).EQ.1) RETURN
        CALL HMWGH(COEFF,ISTAGE)
              RETURN
              END
```

AD-A051 333 RCA GOVERNMENT SYSTEMS DIV MOORESTOWN N J MISSILE AND--ETC F/G 17/9
CCD SIGNAL PROCESSOR STUDY.(U)
DEC 77 L W MARTINSON, B P GAFFNEY, G J MAYER F30602-76-C-0280
UNCLASSIFIED RADC-TR-77-422 NL

4 OF 4
AD
A051 333

END
DATE
FILMED
4-78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
C*
C*      CCD18.FTN
C*
C*
C*       SUBROUTINE COMPUTES THE FILTER RESPONSE PER PULSE
C*
C*
C*
                  SUBROUTINE FILTER(J,IEND)
      REAL AA(30)
      COMMON /FILTER/COEFF(600)
      COMMON /BINSTR/XL(30),IJ(30)
      COMMON /RAND/PI,PII
      COMMON /VOLTS/Q1,Q2,ITIME,IPP,B(30),I2
      COMMON /CCD/CCDW(2,601)
      COMMON /PASS/STAD(20)
C*
        BIAS=STAD(5) + STAD(5)*XL(1)
        ISTAGE=IJ(1)
         INOISE=IJ(8)
        ERR=1. + XL(20)
         SD=XL(17)
        CS=0.
            I1=31
             IK=ISTAGE
             IBEGIN=J
         IF(IBEGIN.GT.ISTAGE) IBEGIN=ISTAGE
      DO 10 I=IEND,IBEGIN
              WELL=CCDW(2,I) - BIAS
        IF(INOISE.EQ.1)  GOTO 9
        IF(SD.LE.0.)  GOTO 9
        IF(I1.LE.30)  GOTO 7
        I1=1
5       READ(1,END=1000,ERR=1000)  AA
7       CONTINUE
        CS=CS + WELL*COEFF(IK)*(ERR + AA(I1)*SD)
            I1=I1 + 1
           GOTO 1010
9     CONTINUE
              CS=CS + WELL*COEFF(IK)
1010          IK=IK - 1
10      CONTINUE
              B(I2)=CS
           I2=I2 + 1
        IF((I2.LT.31).AND.(J.LT.ITIME)) RETURN
           I2=1
         WRITE(2'IPP) B
          IPP=IPP + 1
          RETURN
1000    REWIND 1
        GOTO 5
           END
```

```
C*
C*
C*      CCD20.FTN
C*
C*
        SUBROUTINE SD
      COMMON /BINSTR/XX(30),IJ(20)
      COMMON /PASS/STAD(20),ISTAD(20)
C*
C*
C*      LOADS APPROPRIATE NOISE SOURCES IN SDS
C*
C*
        IF(IJ(8).EQ.1) RETURN
      SDINPT=XX(6)
      SOSHOT=XX(7)
      SDOUTP=XX(9)
      SDINTR=XX(19)
C*
C*      CHECK TO SEE IF ALL SOURCES ARE ADDED IN
C*
             ISTAD(1)=0
             ISTAD(2)=0
             ISTAD(3)=0
        IF(IJ(10).EQ.1)  GOTO 10
             S1=SDSHOT*SDSHOT
             S2=SDINTR*SDINTR
C*
C*     INPUT SD
C*
             STAD(1)=SQRT(SDINPT*SDINPT + S1 + S2)
                ISTAD(1)=1
C*
C*        MIDDLE NOISE SOURCES MINUS TRANSFER
C*
             STAD(2)=SQRT(S1 + 2.*S2)
                  ISTAD(2)=1
C*
C*      OUTPUT NOISE SOURCES
C*
             STAD(3)=SQRT(S1 + S2 + SDOUTP*SDOUTP)
                  ISTAD(3)=1
                RETURN
10      CONTINUE
C*
C*      COMPUTE INPUT IF NEEDED
C*
             VAR=0.
        IF(IJ(11).EQ.1)  GOTO 15
             VAR=SDINPT*SDINPT
             ISTAD(1)=1
15      IF(IJ(12).EQ.1)  GOTO 20
             VAR=VAR + SDSHOT*SDSHOT
             ISTAD(1)=1
20      IF(IJ(16).EQ.1)  GOTO 25
             VAR=VAR + SDINTR*SDINTR
             ISTAD(1)=1
25      IF(ISTAD(1).EQ.1) VAR=SQRT(VAR)
             STAD(1)=VAR
C*
C*
C*      COMPUTE MIDDLE SD IF NEEDED
C*
```

BEST AVAILABLE COPY

```
      VAR=0.
      IF(IJ(12).EQ.1)  GOTO 30
      VAR=SDSHOT*SDSHOT
      ISTAD(2)=1
30    IF(IJ(16).EQ.1)  GOTO 35
      VAR=VAR + 2.*SDINTR*SDINTR
      ISTAD(2)=1
35    IF(ISTAD(2).EQ.1)  VAR=SQRT(VAR)
      STAD(2)=VAR
C*
C*
C*      COMPUTE OUTPUT SD IF NEEDED
C*
      VAR=0.
      IF(IJ(12).EQ.1)  GOTO 40
      VAR=SDSHOT*SDSHOT
      ISTAD(3)=1
40    IF(IJ(14).EQ.1)  GOTO 45
      VAR=VAR + SDOUTP*SDOUTP
      ISTAD(3)=1
45    IF(IJ(16).EQ.1)  GOTO 50
      VAR=VAR + SDINTR*SDINTR
      ISTAD(3)=1
50    IF(ISTAD(3).EQ.1)   VAR=SQRT(VAR)
      STAD(3)=VAR
      RETURN
      END

C*
C*
C*      C5 LINK STRUCTURE
C*
C*
C*    C5,C5<CCD.STB,C5,CCD8,FTNLIB/L/U/E
C*
      CALL OUTP
      CALL RETURN
      END
```

```
C
C         CCD8.FTN
C
C
C         SUBROUTINE PRINTS OUT INITIAL AND FINAL ARRAYS
C
C
                SUBROUTINE OUTP
        REAL A(30),BB(30)
      COMMON /INPUT/ELECTR(1200)
      COMMON /VOLTS/XMAXV,XMAXEL,ITIME,IPP
      COMMON /BINSTR/XZ(30),IJ(2),ILT,IFILT,ILL(3),INOISE,IJL(20)
      COMMON /PASS/STAD(20),ISTAD(20)
      COMMON /CCD/ZL(1200)
      COMMON /FILTER/ARRY(600)
C*
C*
C*     N = # STAGES
C*     VMAXO MAXIMUM OUTPUT VOLTAGES
C*     VMINO MINIMUM OUTPUT VOLTAGES
C*     F  FULL WELL OF ELECTRONS
C*
C*    OUTPUT OF FILTER CAN HAVE A RANGE OF
C*    VALUES OF + TO - N*F*STAGES
C*
C*    VOLTAGE OUT=SLOPE*(ELECTONS + F*STAGES)
C*
C*    ELECTRONS IS # ELECRONS FOR THAT SAMPLE
C*    SLOPE=(VMAXO - VMIN0)/(2*F*STAGES)
C*
C*
                  I2=31
                 VMAXO=48.E-3
                 VMINO=1.E-6
                 X3=FLOAT(IJ(1))*XMAXEL
                X4=X3
         X6=VMAXO/X4
7845     CONTINUE
           IJLL=0
           IPP=0
10       CONTINUE
             J=0
         DO 100 I=1,ITIME
         IF(I2.LE.30)  GOTO 1
           I2=1
         IF(IPP.GT.0)  WRITE(2'IPP) BB
           IPP=IPP + 1
          READ(2'IPP) BB
1        CONTINUE
      IF((XZ(3).LE.0.).AND.(XZ(5).LE.0.))  GOTO 5555
        IF(BB(I2).GT.X4)  BB(I2)=X4
        IF(BB(I2).LT.-X4)  BB(I2)=-X4
        X2=BB(I2)*X6
           BB(I2)=X2
5555       CONTINUE
           I2=I2 + 1
100      CONTINUE
         WRITE(6,8010) IPP
8010     FORMAT(' DONE WITH OUTP'  ,I6//)
          I2=31
         IJLL=IJLL + 1
         IF(IJLL.LT.4)  GOTO 10
           WRITE(2'IPP) BB
```

```
      REWIND 1
      ENDFILE 1
        IPP=1
        I2=31
      IJLL=0
30    CONTINUE
      I2=31
      DO 8079  I=1,ITIME
      IF(I2.LE.30)  GOTO 8078
        I2=1
      READ(2'IPP)  BB
        IPP=IPP + 1
8078  CONTINUE
      IF(IJLL.EQ.0) ELECTR(I)=BB(I2)
      IF(IJLL.EQ.3) ELECTR(I)=ELECTR(I) + BB(I2)
      IF(IJLL.EQ.1) ZL(I)=-BB(I2)
      IF(IJLL.EQ.2) ZL(I)=ZL(I) + BB(I2)
      I2=I2 + 1
8079  CONTINUE
      IJLL=IJLL + 1
      IF(IJLL.LT.4) GOTO 30
        IJR=ITIME
      DO 9157 I=1,ITIME
      ELECTR(I)=SQRT(ELECTR(I)**2 + ZL(I)**2)
9157  CONTINUE
      CALL PLOT1(ELECTR,XMIN,XMAX,AVE,VAR,VAR1,IJR)
        WRITE(5,8075)  IJR,AVE,VAR,XMAX,XMIN
8075  FORMAT(' OUTPUT  #',I6,' AVE ',1PE15.8,' SD ',1PE15.8/
     2 ' HALF THE OUTPUT AVE ',1PE15.8,' SD ',1PE15.8//)
        ENDFILE 2
      IF(ILL(3).NE.0) RETURN
        JK=1
       CALL EPLOT(ELECTR,XMAX,IJR,JX,JK)
            RETURN
            END


C*
C*
C*       C6 LINK STRUCTURE
C*
C*    C6,C6<CCD,STB,C6,CCD26,CCD27,CCD28,CCD29,CCD16,FYNLIB/L/U/E
C*
C*
         CALL SETUP
         CALL RETURN
           END
```

```
C*
C*
C*      LITTLE BOOKKEEPING
C*
C*      CCD26.FTN
C*
C*
C*
              SUBROUTINE SETUP
        REAL ARR(30)
       COMMON /BINSTR/XX(30),IJ(30)
       COMMON /CCD/B(1200)
       COMMON /INPUT/A(1200)
       COMMON /VOLTS/Q1,Q2,ITIME
        IF(IJ(30).EQ.0)  RETURN
        ICC=1
800     CONTINUE
         NUMB=ITIME
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
        WRITE(5,8080) NUMB,AVE,VAR,VAR1
8080    FORMAT(1H1'  #   MEAN   SD   ',I6,4(1X,1PE15.8)/)
        CALL POW2(NUMB,J)
77      CONTINUE
6         CONTINUE
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
            DO 18 I=1,NUMB
             A(I)=A(I) - AVE
18          CONTINUE
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,NUMB)
        WRITE(5,8080) NUMB,AVE,VAR,VAR1
           AVE=1.
        CALL PLOT(A,NUMB,XMIN,XMAX,AVE,AVE,AVE)
          K=1
        CALL EPLOT(A,XMAX,NUMB,K,K)
          IND=2**J
          IPP=IND - NUMB
        IF(IPP.EQ.0)  GOTO 10
          K=NUMB + 1
        DO 7 I=K,IND
7       A(I)=0.
10      DO 20 I=1,IND
        B(I)=0.
20      CONTINUE
        CALL FRXFM(J,A,B)
          IND=IND/2
        DO 30 I=1,IND
         D=A(I)**2 + B(I)**2
          D=SQRT(D)
        A(I)=D
30      CONTINUE
        CALL PLOT1(A,XMIN,XMAX,AVE,VAR,VAR1,IND)
            I=1
        CALL EPLOT(A,XMAX,IND,I,I)
            ICC=ICC + 1
            IW=1
          RETURN
          END
```

BEST AVAILABLE COPY

```
C*
C*
C*     LITTLE BOOKKEEPING
C*
C*     CCD27.FTN
C*
C*
C*
          SUBROUTINE FRXFM(N2POW,XT,YT)
C*
C*     DECIMATION IN FREQUENCY FFT ALGORITHM
C*
C*
       DIMENSION XT(2),YT(2)
       N=2**N2POW
       M=N2POW
       DO 600 L0=1,M
         LMX=2**(M-L0)
         LIX=2*LMX
         SCL=6.2831853072/FLOAT(LIX)
        DO 600 LM=1,LMX
          ARG=FLOAT(LM-1)*SCL
          C=COS(ARG)
          S=SIN(ARG)
         DO 600 LI=LIX,N,LIX
          J1=LI-LIX+LM
          J2=J1+LMX
          T1=XT(J1) -XT(J2)
          T2=YT(J1) - YT(J2)
          XT(J1)=XT(J1) + XT(J2)
          YT(J1)=YT(J1) + YT(J2)
          XT(J2)=C*T1 + S*T2
          YT(J2)=C*T2 - S*T1
600    CONTINUE
C*
C*     BIT REVERSAL
C*
       NV2=N/2
       NM1= N -1
       J=1
       DO 635 I=1,NM1
         IF(I.GE.J) GOTO 631
          T1=XT(J)
          T2=YT(J)
          XT(J)=XT(I)
          YT(J)=YT(I)
          XT(I)=T1
          YT(I)=T2
631      K=NV2
620    CONTINUE
         IF(K.GE.J) GOTO 635
          J=J -K
          K=K/2
          GOTO 620
635    J=J+K
          RETURN
          END
```

```
C!
C*
C*    CCD28.FTN
C*
C*
           SUBROUTINE WGHT(A,IW,NUMB)
      REAL A(2)
      COMMON /RAND/PI,PII
C*
C*
C*
         N=NUMB - 1
         IF(NUMB.NE.2*(NUMB/2)) N=NUMB
         N=N/2 - 1
         CONST=PII/FLOAT(NUMB)
         ALPHA=0.54
         IF(IW.EQ.2)  ALPHA=0.5
         C1=1. - ALPHA
         DO 1 I=1,NUMB
           T1=CONST*FLOAT(I+N)
         A(I)=A(I)*(ALPHA + C1*COS(T1))
1        CONTINUE
            RETURN
            END
```

```
C*
C*
C*      CCD29.FTN
C*
C*
        SUBROUTINE EPLOT(XT,XMAX,LNUMB,LSTRT,LINT)
C       FOR PLOTTING RESULTS ON A SCALE 0 TO 50 DB
C       ASSUMES THAT CAPTIONING IS PROVIDED, AND POINTS EXIST (UP TO LEND)
C       NORMALIZES POINTS TO XMAX BEFORE PLOTTING
C*
C*
C*   XT VECTOR OF STORED POINTS TO BE PLOTTED
C*   XMAX MAX VALUE IN VECTOR XT
C*   LNUMB NUMBER OF POINTS TO BE PLOTTED
C*   LSTRT INDEX OF FIRST POINT TO BE PLOTTED
C*   LINT INTERVAL BETWEEN PLOTTED POINTS IN ARRAY
C*
C*   OUTPUT OF 999 MEAN THAT POINT WAS LESS THEN
C*    OR EQUAL TO ZERO
C*
C*******M27- LATEST RECENSION DATED::21.APR.77
      REAL AKAR(5)
      REAL XT(2)
      COMMON /CCD/ALINE(101)
        DATA AKAR/'.','.','+',' ','O'/
        LEND=LSTRT+(LNUMB-1)*LINT
        KOUNT=0
        WRITE(5,15)
15      FORMAT(//59X,'DB DOWN'/)
        WRITE(5,17)
17      FORMAT(/1X,'PT # VALUE 100 ',17X,'80',18X,'60',18X,'40',
     1   18X,'20',18X,'0 INDEX')
        DO 20 I=LSTRT,LEND,LINT
        TEST=XT(I)/XMAX
        IF(TEST) 24,24,26
24      DB=999.
        GO TO 30
26      DB=-20.*ALOG10(TEST)
30      IF( MOD(KOUNT,10).NE.0 ) GO TO 50
C        EVERY TENTH LINE
        DO 35 J=1,101
35      ALINE(J)=AKAR(1)
        DO 40 J=1,101,5
40      ALINE(J)=AKAR(3)
        GO TO 70
C         ALL OTHER LINES
50      DO 55 J=1,101
55      ALINE(J)=AKAR(4)
        DO 60 J=1,101,10
60      ALINE(J)=AKAR(2)
C        LINE READY FOR INSERTION OF POINT
70      KOUNT=KOUNT+1
        L=101-IFIX(DB+.5)
        IF(L.LT.1) GO TO 90
        ALINE(L)=AKAR(5)
90      WRITE(5,95) I,DB,(ALINE(J),J=1,101),KOUNT
95      FORMAT(1X,I4,F7.2,1X,101A1,I5)
20      CONTINUE
        WRITE(5,17)
        RETURN
        END
```

```
C*
C*
C*      SUBROUTINE PLOTS OUT AN ARRAY ON LINEPRINTER
C*
C*      CCD16.FTN
C*
C*
C*
        SUBROUTINE PLOT(ARRAY,NELMNT,AMIN,AMAX,CONT,DELT,TINTL)
C       ARRAY IS THE ARRAY OF DATA TO BE PLOTTED FROM THE THE 1ST
C       ELEMENT TO THE ELEMENT NUMBER GIVEN BY NELMNT.
C       AMIN IS THE MINIMUN VALUE THE PLOT COULD REACH.
C       AMAX IS THE MINIMUN VALUE THE PLOT COULD REACH.
C       CONT IS A SWITCH THAT TELLS THE SUBROUTINE IF THE INPUT
C       ARRAY IS A CONTINUATION OF THE LAST PLOT.
C       CONT GREATER THAN 1.0 IMPLIES A CONTINUATION.
C       DELT IS THE INCREMENT TO BE USED ALONG THE ABSCISSA.
C       TINTL IS THE INITIAL VALUE OF THE ABSCISSA.
C
C       ***NOTE***
C
C       TINTL IS CHANGED BY THE SUBROUTINE. IT IS RESET TO THE VALUE
C       THAT IS EXPECTED AS THE INITIAL VALUE OF THE NEXT CALL IF THE
C       CONTINUATION OPTION IS USED.
C       IF THE CONTINUATION OPTION IS USED AND THE INITIAL TIME IS CHANGED
C       FROM THE EXPECTED VALUE, THE OUTPUT WILL BE FLAGED WITH A *.
C       THE TIMING WILL BE RESEQUENCED TO AGREE WITH THE NEW VALUE.
C
        DIMENSION ARRAY(5),XS(5),STRING(123)
        DATA SPACE/' '/,STAR/'O'/,GRID/'+'/
         AVE=0.
         VAR=0.
        TINTL=ABS(TINTL)
        DO 1 I=1,123
1       STRING(I)=SPACE
        DO 2 I=12,112,25
2       STRING(I)=GRID
        IF(CONT-1.)3,3,4
3       X=1.001*(AMAX-AMIN)/120.
C       KR GIVES X ROUNDED TO KR SIGNIFICANT DIGITS EQUALS XIN.
        KR=6
        ZP=-69.0775
        Z=AMAX1(ABS(X),EXP(ZP))
        LOG10F=ALOG(Z)/2.302585
        K1=INT(LOG10F+50.)
        PWRK=10.**(50+KR-K1)
        SIGK=AINT(X*PWRK)
        PWRKM1=10.**(49+KR-K1)
        SIGKM1=AINT(X*PWRKM1)
        Y=10.*SIGKM1
        YP=SIGK-Y
        NY=INT(YP)
        NY=((NY)/5+1)*5
        YP=AINT((NY+Y)/10.)
        ROUNDF=YP/PWRKM1
        XIN=ROUNDF
        XIN=X
        AVE=(AMAX+AMIN)/2.
        REVAVE=AINT(AVE/XIN)*XIN
        XMIN=REVAVE-62.*XIN
        XS(1)=REVAVE-50.*XIN
        XS(2)=REVAVE-25.*XIN
```

```
      XS(3)=REVAVE
      XS(4)=REVAVE+25.*XIN
      XS(5)=REVAVE+50.*XIN
      WRITE(5,1000)DELT,TINTL,XS
1000  FORMAT(/5X24HABSCISSA IS IN UNITS OF 1PE13.7,
     1 ' INITIAL VALUE ',1PE13.7/
     2 61X21H------AMPLITUDE------/2X8HABSCISSA5X
     3 1PE11.4,4(14X1PE11.4)/1X,132(1H+))
C*
C*    BY PASS CODE AFTER GOTO 6
C*
      KNT=1
      IF(TINTL.GT.1.) KNT=TINTL
      IF(KNT.GT.0)  GOTO 6
      TSAVE=TINTL
      KNT=1
4     KNTCHK=(TINTL-TSAVE)/DELT+.1
      IF(KNTCHK-KNT)5,6,5
5     WRITE(5,1001)
1001  FORMAT(/2H */)
      KNT=KNTCHK
6     DO 7 I=1,NELMNT
      AVE=AVE + ARRAY(I)
      VAR=VAR + ARRAY(I)*ARRAY(I)
      K=((ARRAY(I)-XMIN)/XIN+2.5)
      IF(K.GT.122)K=123
      IF(K.LT.1)K=1
      TEMP=STRING(K)
      STRING(K)=STAR
      WRITE(5,1002)KNT,(STRING(J),J=2,123)
1002  FORMAT(I10,1X123A1)
      KNT=KNT + 1
7     STRING(K)=TEMP
      TINTL=FLOAT(KNT)*DELT+TSAVE
      XIN=NELMNT
      XMIN=(XIN - 1.)*XIN
      VAR=XIN*VAR - AVE*AVE
      IF(VAR.GT.0.)  VAR=SQRT(VAR/XMIN)
      AVE=AVE/XIN
      WRITE(5,8000) NELMNT,AMIN,AMAX,AVE,VAR
8000  FORMAT(' # OF ELEMENTS ',I5/
     2' MINIMUM VALUE ',1PE15.8/
     3' MAXIMUM VALUE ',1PE15.8/
     4' MEAN OF ELEMENTS',1PE15.8/
     5' SD OF THE ELEMENTS',1PE15.8//)
      RETURN
      END
```

```
C*
C*
C*          CCD LINK STRUCTURE
C*
C*       CCD,CCO,CCD<CCD1,FTNLIB/L/U/E
C*
C*
C*         C0 LINK STRUCTURE
C*
C*       C0,C0<CCD,STB,C0,CCD6,CCD19,CCD31,FTNLIB/L/U/E
C*
C*
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /PASS/STAD(20),ISTAD(22),ROW(7),IRW(4)
1       CONTINUE
         IF(IJ(9).NE.9998)  CALL INSTR
         IF(IJ(21).GT.0)  CALL REPEAT
         IF(IJ(9).LT.0)  GOTO 1
          IJ(21)=IJ(21) + 1
         CALL RETURN
          END
```

BEST AVAILABLE COPY

```
C     CCD6.FTN
C
C
C
C           SUBROUTINE READS IN THE INSTRUCTIONS FOR A RUN
C
C
              SUBROUTINE INSTR
        REAL A(3)
      COMMON /CCD/XPERC,XMEAN,XSD,FCLOCK,FBAND,XZ(4),XLEV,
     2          ZL(20),ISTAGE,IPRINT,ILENGT,IFILT,NRVS,IJ(20)
      COMMON /BINSTR/XXZ(30),IJL(30)
      COMMON /VOLTS/WW1,WW2,ITIME
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      COMMON /RAND/R1(4),RR(6)
        DATA A/4HTEMP,4H02.D,4HAT00/
          IJL(21)=0
          IRW(3)=0
          IJL(9)=9998
        WRITE(6,7000)
7000    FORMAT(' CREATE NEW FILE ON DAT SLOT 2 Y=0 N=1 '/)
        READ(6,91) I
        IF(I.NE.0) GOTO 7005
        WRITE(6,7001)
7001    FORMAT(' NAME OF FILE XXXXXX.D '/)
        READ(6,7002) A(1),A(2)
7002    FORMAT(2A4)
7005    WRITE(5,7003) A
7003    FORMAT(' NAME OF FILE FOR THIS RUN ',3A4//)
        CALL SETFIL(2,A,IER2,'DK',0)
        DEFINE FILE 2(50,64,U,IVAR)
1       WRITE(6,100)
100     FORMAT(' THE NUMBER OF STAGES IN THE CCD (F10.0)'//)
        READ(6,101) X
101     FORMAT(F10.0)
             IUPPER=600
             ILOWER=0
             ISTAGE=X
        IF((ISTAGE.GT.ILOWER).AND.(ISTAGE.LE.IUPPER))  GOTO 3
          WRITE(6,201) ISTAGE,ILOWER,IUPPER
201     FORMAT(' ERROR MESSAGE  # OF STAGES TO SMALL OR TO LARGE'/
     2' # OF STAGES:  ',I4,'  LOWER LIMIT:  ',I4,' UPPER:  ',I4//)
             GOTO 1
3       WRITE(6,103)
103     FORMAT(' SD OF THE INITIAL STATE (F10.0) '/
     2' IF < 0 THEN NO BACKGROUND VOLTAGE ADDED '/)
        READ(6,101) XSD
C*
C*
C*      CHANGE 02/22/77
C*
        XXZ(3)=XSD
        IJL(1)=ISTAGE
4       WRITE(6,104)
104     FORMAT(' SURFACE OR BURIED DEVICE (0 OR 1.)'/)
        READ(6,101) ZZ1
        IJ(1)=ZZ1
        IJL(6)=IJ(1)
        IF((IJ(1).LT.0).OR.(IJ(1).GT.1)) GOTO 4
        WRITE(6,108)
108     FORMAT(' AREA OF WELL IN MIL**2 '/)
        READ(6,101) ZL(5)
        WRITE(6,107)
```

```
107       FORMAT(' % OF BACKGROUND CHARGE '/
     2    '  <0 THEN SPECIFY TRANSFER LOST '/)
          READ(6,101) ZL(6)
          IF(ZL(6).LT.0.) WRITE(6,7891)
7891      FORMAT(' FRACTION LOST EACH TIME .XXXX'/)
          IF(ZL(6).LT.0.) READ(6,101)  XPERC
          IF(ZL(6).GE.0.) CALL CTI(ZL,XPERC,%J)
          WRITE(6,109)
109       FORMAT(' CLOCK SWING VOLTAGE '/)
          READ(6,101) ZL(8)
          XXZ(1)=XPERC
          XXZ(15)=ZL(5)
          XXZ(16)=ZL(6)
          XXZ(18)=ZL(8)
          WRITE(6,9050)
9050      FORMAT(' PLOT OF INPUT AND OUTPUT Y=0 N=1 '/)
          READ(6,91) IJL(7)
          WRITE(6,7011)
7011      FORMAT(' FFT OF OUTPUT  Y=1 N=0 '/)
          READ(6,91) IJL(30)
5         WRITE(5,1000) ISTAGE,XPERC,ZL(6),ZL(5)
1000      FORMAT(' # OF STAGES IN THE CCD ',I5/
     3'   CTI OF DEVICE ',1PE15.8/
     4'   % OF THE BACKGROUND CHARGE ',1PE15.8/
     4'   AREA OF THE WELL (MIL**2)',1PE15.8//)
6         WRITE(6,206)
206       FORMAT(' CLOCK FREQUENCY (F10) '/)
             CLCKMX=1.E10
          READ(6,101) FCLOCK
        IF((FCLOCK.GT.0.).AND.(FCLOCK.LE.CLCKMX)) GOTO 60
          WRITE(6,1006) CLCKMX
1006      FORMAT(' CLOCK RATE OUTSIDE OF RANGE OF 0. TO 'F10.0/)
                GOTO 6
60        CONTINUE
          WRITE(5,701)  FCLOCK
701       FORMAT('    CLOCK RATE   ',1PE15.8/)
80        WRITE(6,800)
800       FORMAT(' THE LENGTH OF TIME OF THE RUN < 1201 '/)
          READ(6,101) ZZ1
            ITIME=ZZ1
          IF((ITIME.LT.0).OR.(ITIME.GT.1200))   GOTO 80
          WRITE(6,90)
90        FORMAT(' PRINT OUT INTERMEDIATE VALUES NO=0 YES=1'/)
          READ(6,91) IPRINT
91        FORMAT(I1)
          WRITE(6,9008)
9008      FORMAT(' FEEDTHROUGH VOLTAGE ADDED TO OUTPUT N=0 Y=1'/)
C*
C*        MAXIMUM INPUT VOLTAGE IS 2.8 VOLTS
C*
C*
          XXZ(4)=FCLOCK
          IJL(2)=IPRINT
               XMAXV=2.8
               WW1=XMAXV
          READ(6,91)     NRVS
96        WRITE(6,93)
93        FORMAT(' DURATION OF THE SIGNAL MIN=0 MAX=1200'/)
          READ(6,101) ZZ1
          ILENGT=ZZ1
          WRITE(6,7020)
7020      FORMAT(' TYPE OF SIGNAL PULSE =0 SIN = 1 '/)
          READ(6,91) IJL(29)
          IF(IJL(29).EQ.0)  GOTO 95
7022      WRITE(6,7021)
7021      FORMAT(' # OF SINUSOIDALS  F10. < 5'/)
```

```
      READ(6,101) ZZ1
      IJL(28)=ZZ1
      IF((IJL(28).LE.0).OR.(IJL(28).GT.4))  GOTO 7022
      IKK=IJL(28)
      IKL=30
      DO 7023 I=1,IKK
      WRITE(6,7024) I
7024  FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL(HERTZ)'/)
      READ(6,101) ZZ1
      XXZ(IKL)=ZZ1
      WRITE(6,8025) I
8025  FORMAT(' AMPLITUDE (% OF WELL) OF THE ';I3,' SIGNAL'/)
      READ(6,101) STAD(I)
      STAD(I)=WW1*STAD(I)/100.
      WRITE(5,7030) I,ZZ1,STAD(I)
7030  FORMAT(' FREQUENCY OF THE ',I3,' SIGNAL ',1PE15.8/
     2 ' AMPLITUDE (VOLTS) OF THE SIGNAL ',1PE15.8/)
      IKL=IKL - 1
7023  CONTINUE
      WRITE(6,8053)
8053  FORMAT(' DC BIAS (% OF WELL) TERM ADDED TO INPUT F10 '/)
      READ(6,101) XXZ(5)
       XXZ(5)=WW1*XXZ(5)/100.
          GOTO 9918
95    CONTINUE
      WRITE(6,92) XMAXV
92    FORMAT(' INPUT LEVEL OF SIGNAL  MAX= ',F10.3,' VOLTS'/)
      READ(6,101) XLEV
      IF((XLEV.LE.0.).OR.(XLEV.GT.XMAXV)) GOTO 95
9918  CONTINUE
      IJL(3)=ILENGT
      IJL(5)=NRVS
      XXZ(10)=XLEV
      WRITE(6,8010)
8010  FORMAT(' NON LINEAR INPUT WARPING Y=0 N=1'/)
      READ(6,91) IJ(12)
      WRITE(6,97)
97    FORMAT(' FILTER RESPONSE COMPUTED? N=0 Y=1'/)
      READ(6,101) ZZ1
      IFILT=ZZ1
      IJL(20)=1
      WRITE(6,9033)
9033  FORMAT('  DARK CURRENT ADDED Y=0 N=1 '/)
      READ(6,91) IJ(13)
      IF(IJ(13).EQ.1)  GOTO 9036
       WRITE(6,9034)
9034  FORMAT(' AMBIENT TEMPERATURE DEGREES C '/)
       READ(6,101) ZZ1
       XXZ(26)=ZZ1 + 273.
      WRITE(5,9035) ZZ1,XXZ(26)
9035  FORMAT(' AMBIENT TEMPERATURE (C) ',F10.4,'  (K) ',F10.4/)
      WRITE(6,1701)
1701  FORMAT(' DO YOU WANT TO HOLD THE SIGNAL FOR ANY '/
     2 ' OF TIME Y=0 N=1 '/)
      READ(6,91) IJL(20)
      IF(IJL(20).EQ.1)  GOTO 9036
      WRITE(6,1702)
1702  FORMAT(' TIME(SEC) LEFT IN DELAY LINE '/)
      READ(6,101) XXZ(21)
      WRITE(6,1703)
1703  FORMAT(' FREQUENCY CLOCK SIGNAL OUT AT '/)
      READ(6,101) XXZ(22)
      WRITE(5,1704) XXZ(4),XXZ(21),XXZ(22)
1704  FORMAT(' INPUT SAMPLING RATE '1PE15.8,
     2 ' TIME LEFT IN DEVICE ',1PE15.8,
     3 ' OUTPUT SAMPLING RATE ',1PE15.8/)
```

```
9036    CONTINUE
        IJL(4)=IFILT
        IJL(17)=IJ(12)
        IJL(18)=IJ(13)
        WRITE(6,6011)
6011    FORMAT(' MULTIPLE RUN Y=# OF CHANGES N=0 F10'/)
        READ(6,101) ZZ1
        IJL(19)=ZZ1
        IF(IJL(19).EQ.0)  GOTO 8000
        WRITE(6,6012)
6012    FORMAT(' WHICH INPUT IS TO BE CHANGED '/
     2  ' 1= # OF STAGES, 2=SURFACE/BURIED '/
     3  ' 3= AREA OF WELL, 4=STORAGE TIME (SEC) '/
     4  ' 5=CLOCK FREQUENCY,6=AMBIENT TEMPERATURE '//)
        READ(6,91) IJL(22)
          K=IJL(19)
        DO 6019 I=1,K
          WRITE(6,6013) I
6013    FORMAT(' INPUT THE ',I6,' VALUE '/)
          READ(6,101) RR(I)
6019    CONTINUE
          WRITE(5,6015) (I,RR(I),I=1,K)
6015    FORMAT(' MULTIPLE RUNS '//7(1X,I2,2X,1PE15.8))
          WRITE(6,8717)
8717    FORMAT(' SECOND VARIABLE CHANGING Y=# N=0 '/)
        READ(6,91) IRW(1)
        IF(IRW(1).EQ.0)  GOTO 8000
        WRITE(6,6012)
        READ(6,91) IRW(2)
        K=IRW(1)
        DO 8718 I=1,K
        WRITE(6,6013) I
        READ(6,101)  ROW(I)
8718    CONTINUE
        WRITE(5,6015)  (I,ROW(I),I=1,K)
8000    WRITE(6,8001)
8001    FORMAT(' RUN WITH NOISE Y=0 N=1 '/)
        READ(6,91) IJ(3)
        IJL(8)=IJ(3)
        IF((IJ(3).LT.0).OR.(IJ(3).GT.1))  GOTO 8000
        IF(IJ(3).EQ.1)   RETURN
          K=10
        DO 9000 I=5,11
         IJ(I)=0
         IJL(K)=0
          K=K + 1
9000    CONTINUE
        WRITE(6,8003)
8003    FORMAT(' SELECT THE PARTICULAR NOISE INPUTS N=0,Y=1'/)
        READ(6,91) IJ(5)
        IJL(10)=IJ(5)
        IF(IJ(5).EQ.0)  RETURN
        WRITE(6,8004)
8004    FORMAT(' ADD IN INPUT NOISE Y=0 N=1 '/)
        READ(6,91) IJ(6)
        WRITE(6,8005)
8005    FORMAT(' ADD IN THE SHOT NOISE Y=0 N=1'/)
        READ(6,91) IJ(7)
        WRITE(6,8006)
8006    FORMAT(' ADD IN THE TRANSFER NOISE Y=0 N=1'/)
        READ(6,91) IJ(8)
        WRITE(6,8007)
8007    FORMAT(' ADD IN THE OUTPUT NOISE Y=0 N=1'/)
        READ(6,91) IJ(9)
        WRITE(6,8008)
8008    FORMAT(' ADD IN THE FILTER NOISE Y=0 N=1'/)
```

```
      READ(6,91) IJ(10)
      WRITE(6,8009)
8009  FORMAT(' ADD IN INTERFACE NOISE '/)
      READ(6,91) IJ(11)
         K=11
      DO 57 I=6,11
      IJL(K)=IJ(I)
      K=K + 1
57    CONTINUE
                 RETURN
                 END

C*
C*
C*     CCD19.FTN
C*
C*
C*      COMPUTES CTI FOR SURFACE AND BURIED DEVICES
C*
C*       02/22/77
C*
C*
       SUBROUTINE CTI(ZL,ZPERC,IJ)
     INTEGER IJ(5)
     REAL ZL(20)
       X=ZL(6)
     IF(IJ(1).EQ.1)   GOTO 100
      IF(X.GT.4.) GOTO 1
       ZPERC=3.6E-4
       RETURN
1     IF(X.GT.5.) GOTO 2
        ZPERC=-2.7E-4*X + 1.4E-3
        RETURN
2      IF(X.GT.10.) GOTO 3
        ZPERC=-1.E-5*X + 1.4E-4
        RETURN
3       ZPERC=3.9E-5
        RETURN
100    IF(X.GT.4.)  GOTO 101
        ZPERC=-1.6E-5*X + 1.1E-4
        RETURN
101    IF(X.GT.13.5) GOTO 102
        ZPERC=-2.1E-6*X + 5.8E-5
        RETURN
102     ZPERC=2.8E-5
        RETURN
        END
```

BEST AVAILABLE COPY

```
C*
C*
C*
C*      CCD31.FTN
C*
C*
C*
            SUBROUTINE REPEAT
      REAL A(3)
      COMMON /BINSTR/XX(30),IJ(30)
      COMMON /RAND/R1(4),RR(6)
      COMMON /PASS/STAD(20),ISTAD(20),IVAR,IVAR1,ROW(7),IRW(4)
      DATA A/4HTEMP,4H02.D,4HAT00/
        CALL SETFIL(2,A,IER2,'DK',0)
        DEFINE FILE 2(50,64,U,IVAR)
        IF(IJ(21).GT.IJ(19))  GOTO 1000
            K=IJ(22)
           KK=IJ(21)
        CALL FINDER(RR,Y,K,KK)
      IF((IJ(21).EQ.1).AND.(IRW(3).EQ.0))  ROW(7)=Y
             RETURN
1000    CONTINUE
        IRW(3)=IRW(3) + 1
        IF(IRW(3).GT.IRW(1))  GOTO 2000
          K=IRW(2)
         KK=IRW(3)
        CALL FINDER(ROW,Y,K,KK)
          K=IJ(22)
         KK=7
          IJ(21)=0
         CALL FINDER(ROW,Y,K,KK)
           RETURN
2000    CONTINUE
            IJ(9)=-10000
           RETURN
             END
```

MISSION
of
Rome Air Development Center

RADC plans and conducts research, exploratory and advanced development programs in command, control, and communications (C^3) activities, and in the C^3 areas of information sciences and intelligence. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

AMERICAN REVOLUTION BICENTENNIAL 1776-1976